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Energy Storage and Dissipation in Polyurea Composites

by

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B.S. Chemical Engineering

University of Illinois at Champaign-Urbana, 2002

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of

Naval Engineer

and

Master of Science in Mechanical Engineering

at the Massachusetts Institute of Technology

June 2013

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Submitted to the Department of Mechanical Engineering

on May 14, 2013, in partial fulfillment of the

requirements for the degrees of Naval Engineer and

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ABSTRACT

Polyurea composites have been of interest for a variety of engineering applications via their highly dissipative yet resilient behavior under deformation. Polyurea composites have been considered as a self-healing and anticorrosion coating in building applications, and more interestingly, as a lightweight addition to steel armor. In combination with a metal plate, a polyurea layer has been extensively studied under impact and blast loading. In this research, the tunable performance of polyurea sandwich armor composites is explored in modeling and experimentation. Cylindrical arrays comprised of polyurea, a resilient yet dissipative material, enable improved load transmission by utilizing new dissipation and storage pathways due to geometry. Experimentation and computational modeling are used to quantify the dissipation features of the polyurea composite. This research combines a new polyurea interlayer geometry with steel to improve the composite armor blast performance by increasing energy dissipation.

Thesis Supervisor: Mary C. Boyce

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Table of Contents

Introduction	11
Traditional Steel Armor	11
Modern Composite Armor	12
Polymer Coatings.....	12
Steel Armor with Polymer Coating	12
Steel-Polymer Sandwich Armor.....	13
Overview	14
Background	15
Threat of Concern.....	15
Blast Wave	15
Projectile Impact.....	16
Mechanisms of Energy Dissipation in Steel and Polymers.....	16
Inelastic Deformation	17
Energy Absorption in Composite Armor	17
Blast.....	17
Projectile Impact.....	18
Material Properties of Armor Components.....	18
Steel	18
PSM4	19
Polyurea.....	20
Material Models of Armor Components.....	22
Steel	22
PSM4	23
Polyurea.....	25
PSM4 Array Compression	29
Materials and Methods	29
Fabrication and Mechanical Testing	29
Array Void Fraction	29
Finite Element Model.....	31
Experimental and Simulated Response	32
Small Cylinder Arrays	32
Large Cylinder Experiments	41
Comparison of Large Array and Small Array.....	43
Effects of Lateral Array Constraints	44
Effect of Compression on Void Fraction	47
Conclusions	48
Polyurea Array Compression	51
Materials and Methods	51
Fabrication and Mechanical Testing	51
Finite Element Model.....	51
Experimental and Simulated Response	52
Small Cylinder Arrays	52
Solid Equivalent Arrays	65
Energy Dissipation	68
Conclusions	71
Improved Composite Armor Under Blast Loading.....	73

Materials and Methods	73
Finite Element Model.....	73
Simulated Composite Armor Response	74
Conclusions	81
Summary and Conclusions	85
Conclusions	85
Future Work.....	85
Appendix A: Sample Production.....	91

Table of Figures

Figure 1: Underwater explosion incident on steel plates with varying thickness of PU coating.....	13
Figure 2: Explosive generated pressure wave from 1 kg TNT	16
Figure 3: PSM4 stress-strain behavior showing highly elastic large strain behavior.....	19
Figure 4: Strain rate stiffening of polyurea reprinted with permission.....	20
Figure 5: PU 1000 stress-strain behavior showing energy storage and dissipation.....	21
Figure 6: DMA (1 Hz) Isochronal plots of PU between -100 and 150 °C reprinted with permission	21
Figure 7: PSM4 experimental and simulated stress-strain using compressible Neo Hookean model	25
Figure 8: PU Cylinder Compression Is Strain-Rate Dependent.....	26
Figure 9: Uniaxial compression using the constitutive model for PU and experimental data at 0.1/s	28
Figure 10: 1-row void dimensions	29
Figure 11: 2-row void dimensions	29
Figure 12: 3-row void dimensions	30
Figure 13: PSM4 array finite element models for 1, 2, and 3-rows.....	32
Figure 14: PSM4 array of cylinders shown in uncompressed state.....	33
Figure 15: PSM4 array of cylinders uncompressed with FE simulation overlay	33
Figure 16: PSM4 array of cylinders in fully compressed state	33
Figure 17: PSM4 array uncompressed state with FE simulation overlay	34
Figure 18: Experimental and simulated data for 1, 2 and 3-rows of PSM4	34
Figure 19: PSM4 array effective stress-strain curve.....	35
Figure 20: PSM4 1-row array strain field comparison (ϵ_{xx}) of experiment and simulation.....	36
Figure 21: PSM4 1-row array strain field comparison (ϵ_{xy}) of experiment and simulation.....	37
Figure 22: PSM4 1-row array strain field comparison (ϵ_{yy}) of experiment and simulation.....	38
Figure 23: PSM4 2-row array strain field comparison (ϵ_{xx}) of experiment and simulation.....	39
Figure 24: PSM4 2-row array strain field comparison (ϵ_{xy}) of experiment and simulation.....	40
Figure 25: PSM4 2-row array strain field comparison (ϵ_{yy}) of experiment and simulation.....	41
Figure 26: Experimental and simulated data for 1 and 2-rows of large PSM4 cylinders.....	42
Figure 27: PSM4 large cylinder array--note PMMA spacer on right.....	42
Figure 28: PSM4 large cylinder array uncompressed with FE overlay	43
Figure 29: PSM4 large array under full compression	43
Figure 30: PSM4 large array under full compression with simulated deformed array overlay	43
Figure 31: Effective stress-strain comparison of large and small PSM4 arrays	44

Figure 32: Contact radius resulting from flat plate compression based on Hertz equation for a cylinder	45
Figure 33: Experimental constrained array vs. unconstrained simulated array using Hertz equation	46
Figure 34: Deformation of fully constrained compression	46
Figure 35: Void and slope change compared with compressive force on 1, 2, and 3-row arrays	47
Figure 36: PSM4 experimental effective stress-strain curve	48
Figure 37: Polyurea array simulation mesh for 1,2, and 3-rows	52
Figure 38: Polyurea cylinder array uncompressed	53
Figure 39: Polyurea cylinder array uncompressed with FE overlay	53
Figure 40: Polyurea cylinder area in the compressed state	53
Figure 41: Polyurea cylinder array compressed with FE overlay	54
Figure 42: 2-row polyurea array in compressed state with FE overlay	54
Figure 43: 3-row polyurea array in compressed state with FE overlay	54
Figure 44: Polyurea array compression experiments	55
Figure 45: Polyurea array compression experiments with FE simulations	56
Figure 46: Effective stress-strain curves for PU array compression for 1,2, and 3-rows	57
Figure 47: Polyurea 1-row array strain field ϵ_{xx}	58
Figure 48: Polyurea 1-row array strain field ϵ_{xy}	59
Figure 49: Polyurea 1-row array strain field ϵ_{yy}	60
Figure 50: Polyurea 2-row array strain field ϵ_{xx}	61
Figure 51: Polyurea 2-row array strain field ϵ_{xy}	62
Figure 52: Polyurea 2-row array strain field ϵ_{yy}	63
Figure 53: Polyurea 3-row array strain field ϵ_{xx}	64
Figure 54: Polyurea 3-row array strain field ϵ_{yy}	65
Figure 55: Polyurea 1-row equivalent solid shown uncompressed and compressed	66
Figure 56 Polyurea 2-row equivalent solid shown uncompressed and compressed	66
Figure 57: Polyurea 1 and 2-row equivalent solid samples under compression	67
Figure 58: Polyurea 1 and 2-row equiv. solid tests with 1-row equiv. FE	67
Figure 59: Two loading and unloading cycles for polyurea under uniaxial compression	68
Figure 60: Two loading and unloading cycles for 1-row constrained array	69
Figure 61: Two loading and unloading cycles for 2-row constrained array	69
Figure 62: Two loading and unloading cycles for 3-row constrained array	70
Figure 63: Polyurea array dissipation density for 1,2 and 3-row arrays	71
Figure 64: Array effective stress-strain response for 1, 2 and 3-rows	71
Figure 65: Simulation geometry of solid Polyurea composite armor	74
Figure 66: Deflection of solid polyurea composite armor under blast loads	75
Figure 67: Solid polyurea interlayer with 1/2 kg TNT	75
Figure 68: Solid polyurea interlayer with 1 kg TNT	76
Figure 69: Solid polyurea interlayer with 2 kg TNT	77

Figure 70: Simulation geometry of cylindrical array polyurea composite armor	78
Figure 71: Deflection of 1-row polyurea composite armor under blast loads	78
Figure 72: Cylinder polyurea interlayer with 1/2 kg TNT	79
Figure 73: Cylinder polyurea interlayer with 1 kg TNT	79
Figure 74: Cylinder polyurea interlayer with 2 kg TNT	80
Figure 75: Plastic dissipation and strain energy of the top steel layer in two composite armor configurations	80
Figure 76: Comparison of top plate deflection of two sandwich composite armor geometries	82
Figure 77: Comparison of bottom plate deflection of two sandwich composite armor geometries	82
Figure 78: PSM4 Sheet	91
Figure 79: PU Sample Stock	92
Figure 80: Top down view of PU sample stock	92
Figure 81: Polyurea sample preparation	92
Figure 82: Front fixture face	93
Figure 83: Fixture with metal wire bracing and C-clamp	94
Figure 84: Large sample fixture	95
Figure 85: Zwick Testing Machine	96
Figure 86: Material characterization with and without barreling	96

Chapter 1

Introduction

Traditional Steel Armor

From the days of sail until World War II, naval combatants were armored to reduce the damage caused by ballistic trajectory projectiles fired from cannons and guns (Corbett, 1918). Warships were designed to trade damage with the enemy. The current use of much higher power precision guided missiles reduces the effectiveness of armor. The response to these overmatching threats has been to merely isolate the damaged and flooded compartments, and attempt to keep the ship afloat. Consequently, modern naval combatants do not have significant armored personnel protection beyond the structural steel. The structure of the ship is primarily designed with sufficient strength requirements to survive waves crashing on the deck, and worse case deck/keel stresses. The most common naval construction material is the low alloy steel designated DH-36 (Ships Design Standard 100).

Attacks on US naval warships in the last 25 years have been conducted with low technology and low cost bulk explosive charges. USS Samuel B. Roberts was operating in international waters and detonated a mine that caused significant damage in 1988 (Peniston, 2006). A 5m hole was ripped in the underside of the hull. Terrorists rammed the USS Cole during a port stop with an explosive filled boat in 2000 (Stone, 2012). A 12m hole was cut into the hull of the Cole at the waterline. Both attacks caused sufficient damage to the unarmored ships that they narrowly avoided sinking (Peniston, 2006; Stone, 2012).

Sufficient steel armor can be added to prevent rupture of the hull but at a large addition in weight. Multiple options exist for improving the blast protection for the roughly 300 operational warships (OPNAV N8, 2013). Some options include adding an explosive resistant polymer coating to the interior of the hull, adding exterior steel to create a thicker solid hull, adding a double hull with an air/seawater gap, or adding a double hull with a polymer interlayer. Doubling the hull thickness below

the waterline by adding a 1 cm thick addition to the hull of the USS Cole would weigh 265 MT. This is only a 3% increase in the ships total weight, but the ship will pay a fuel penalty to haul this extra weight over a 30-year operational life. The lightest composite armor that can still defeat the simple blast threat results in a lighter ship or more offensive capability.

Modern Composite Armor

Polymer Coatings

The military has studied polymer coatings for several years. Polyurea has emerged as one of the best polymers due to its toughness, resilience, and dissipation. It is of interest as a coating for concrete buildings to improve safety under blast loading (Porter et al., 2011). Polyurea coatings are currently used in a Marine Corps body armor and vehicle armor (Eubanks, 2012). It is considered as a self-healing tank coating and has fire resistant properties. The Office of Naval Research (ONR) has funded research on the use of polyurea as an explosive resistant coating for several years (Barsoum et al., 2009).

Steel Armor with Polymer Coating

Composite armor, which includes layers of different materials, frequently shows an improvement in ballistic resistance with a reduction in weight over solely metallic armor. Roland et al conducted impact experiments comparing a single steel plate against one coated with polyurea (Roland et al., 2010). They found that despite the negligible increase in weight of the polyurea coating, there was an increase of over 60% in the ballistic limit. It was also found that the equivalent ballistic protection would require twice the weight if using only steel. In another experiment it was found that when 11.2mm of polyurea was added to a 4.8mm plate of DH-36 it improved the ballistic limit for pointed impactors by 42% over a steel plate alone (Xue et al., 2010). Interest in composite polymer armor has also grown in recent years after numerous successful tests under blast loading. In several tests, polyurea

added to the backside of a metal plate showed improved fracture resistance from blast by changing the failure mechanism of the metal (Ackland et al., 2013; Amini et al., 2010)

The US Department of Defense through the Advanced Materials, Manufacturing, and Testing Information Analysis Center (AMMTIAC) has tested polyurea coatings on steel plates against blast loading underwater. Figure 1 shows the damage to three steel plates sustained from an underwater blast load. An identical explosive charge was used on each plate. The leftmost plate had no polyurea coating while the middle and right plates had 5/8" and 1" respectively. The 5/8" coating reduced the size of the rupture while the 1" coating prevented rupture (Barsoum et al., 2009).



Figure 1: Underwater explosion incident on steel plates with varying thickness of PU coating

Figure 1 courtesy of AMMTIAC: reprinted with permission

Steel-Polymer Sandwich Armor

Several tests have included a composite armor with a polyurea interlayer (Tekalur et al., 2008; Bahei-El-Din et al., 2006). Tekalur et al. used E-glass vinyl ester outer layers with a polyurea interlayer and showed the polyurea protected the stiff outer layers and improved blast performance by 100% for a 60% weight addition over the outer layers alone. Bahei-El-Din et al. showed that the addition of polyurea to other ductile interlayers reduced the peak kinetic energy of the armor by 50%. Both tests have been limited to the analysis of a solid layer of polyurea. There may be room to improve on the energy absorption and dissipation of steel-polymer sandwich armor by considering a new interlayer geometry.

Overview

This thesis presents a possible improvement to a composite armor panel with a polyurea interlayer. A potential application of this interlayer configuration is the improvement of energy absorption and dissipation in composite sandwich armor for fragmentation and blast protection (Tekalur et al., 2008). Initially, experimental and numerical analyses of polymeric materials that exhibit tunable large strain mechanical behavior are considered. Specifically, the use of geometric structuring is compared with a homogeneous solid material in a sandwich armor composite. A simple elastomer, PSM4, is used to develop the basic response of close packed cylinder arrays under compression. PSM4 exhibits highly elastic large strain deformation behavior with little hysteresis (Bertoldi et al., 2008), while polyurea has rate sensitivity, viscoelasticity, viscoplasticity, and resilience (Yi et al., 2006). Finally, a common low alloy steel used in ship construction, DH-36, is modeled in simulations from extensive data in the literature for use in composite armor simulations.

The energy absorption and dissipation characteristics of steel-polymer sandwich armor are investigated using numerical simulations under several blast loads. A finite element model was developed in which constrained arrays of cylinders were compressed with varying void fractions. Experimental models were constructed and tested to validate the numerical material and geometric models. The analysis of these experimental and numerical models provide insight into the dissipation and storage of energy in the sandwich armor panel and aid in finding the optimal interlayer geometry.

Chapter 2

Background

Threat of Concern

Blast Wave

Most modern offensive weapons do not rely exclusively on kinetic energy to inflict damage. The weapons magnify the damage by converting chemical energy stored in the explosive into mechanical energy. When detonated, the explosive creates a rapid expansion of gases that bursts the casing and creates a shock wave.

The peak pressure is reached very quickly as the shock wave passes, after which the pressure subsides. Steel is damaged from the pressure wave via plastic deformation, and both ductile and brittle fracture. Polymer damage can occur through fracture or tearing from elongation. Most of the energy from the explosive is released in both a pressure wave and high velocity casing fragments (Federation of American Scientists, 1998). High velocity fragments can deform or perforate both steel and polymers.

The pressure wave is most simply modeled with the Friedlander waveform (Dewey, 1963)

$$P(t) = P_s e^{-\frac{t}{t^*}} \left(1 - \frac{t}{t^*}\right) \quad (1)$$

Where P_s is the maximum pressure immediately behind the wave front, t is the time as measured from the shock wave arrival, and t^* is the time the pressure returns to ambient. An explosive, such as TNT, has a super-sonic detonation velocity of 7000 m/s (Brode, 1965). The resulting pressure wave of 1kg of TNT measured 1m from the detonation point produces the pressure wave shown in Figure 2.

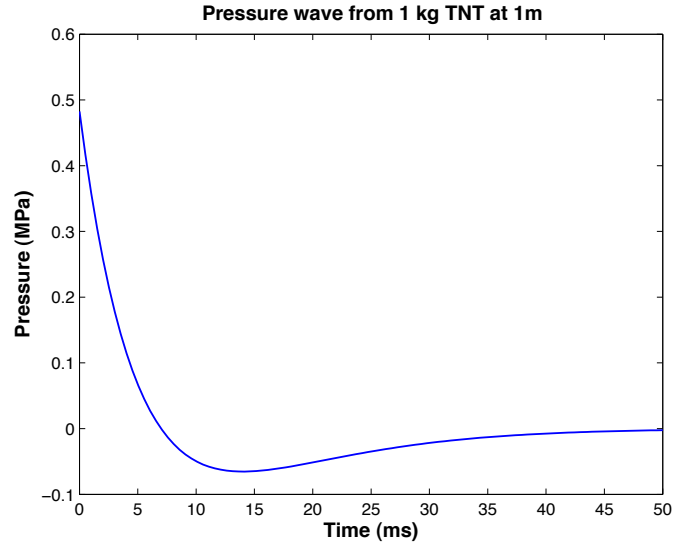


Figure 2: Explosive generated pressure wave from 1 kg TNT

The peak pressure experienced falls off as $1/r^3$ as the wave expands spherically in space. The incident blast wave results in very high strain rates.

Projectile Impact

Warheads generate a quantity of fragments based on the warheads objective. The velocity of the fragments can be calculated using equation 2.

$$v = \sqrt{2\Delta E} \sqrt{\frac{C/M}{1+K(\frac{C}{M})}} \quad (2)$$

In this equation, $\Delta E = 2.715 \times 10^6 \frac{\text{J}}{\text{kg}}$ for TNT, C/M is the charge to fragmenting weight ratio, and K is the shape value of 0.5 for a cylinder (Federation of American Scientists, 1998). The most frequently used general-purpose bombs and warheads can be estimated to have a fragmentation size and velocity comparable with a .50 caliber Browning Machine Gun (BMG) rifle round or 50-gram projectile at 1000 m/s.

Mechanisms of Energy Dissipation in Steel and Polymers

Armor is used to provide protection for personnel and equipment from blast waves and high velocity projectiles. The armor is designed to absorb the kinetic energy of the blast wave or fragment and reduce the remaining energy in order to mitigate

harm to the object being protected. The armor can absorb the impact energy and dissipate it through a variety means.

Inelastic Deformation

The plasticity exhibited by steel and some polymers cause the material to undergo a permanent deformation. In metals, it is a shear-dominated phenomenon that occurs where the underlying deformation mechanism are dislocations that glide along crystallographic slip planes. Polymer plasticity is also shear dominated. Plastic deformation occurs when the intermolecular barriers to yield are overcome by the stress. Plastic deformation is caused by shear stresses generated in the material as it absorbs the ballistic or blast loading. The work done in plastic deformation dissipates the energy of the impact. An additional form of dissipation in polymers is the viscous component of viscoelastic deformation, which is also associated with hysteresis loops. Hysteresis loops give the energy dissipated during loading and unloading of an elastomer. The energy is lost through internal friction.

Energy Absorption in Composite Armor

Composite armor is designed to deform when attacked by a high energy impulse. This type of armor has a lower density than a monolithic steel plate and requires a greater deformation to absorb an equivalent amount of energy. The composite armor considered here is designed for energy absorption from blast waves and non-penetrating projectiles.

Blast

Energy is transferred from an incident pressure wave to the metal armor through plastic deformation. For a given thickness and hardness of metal, lower energy blasts tend to create dents while higher energies rip the metal through shearing.

Some polymers, such as polyurea, have a large failure strain and can undergo significant elongation before failure (Roland et al., 2010). If the blast first encounters steel, the polymer behind it stretches and provides a cushion to improve the failure response of the steel. As the elongation increases, the dissipated energy

also increases (Yi et al., 2006). The layering of the polymer with the steel also distributes the loading to the steel differently, in a less localized manner, which enables the steel to undergo plastic deformation over more the volume of the steel and hence increase the ability of the steel to dissipate the energy of the threats, whether ballistic or blast.

Projectile Impact

Non-penetrating projectiles result in a local or global dent in the outer metal plate. Fracture and spalling can also occur in harder metals. More ductile metals like DH-36 tend to deform plastically rather than experiencing brittle fracture or spalling (Klepaczko et al., 2009). As the metal thins in the region of the dent, the polymer layer beneath it acts as a shock absorber to spread the initial impact impulse over a greater area of the steel. Composite armors that maximize polymer deformation absorb and dissipate the most energy.

Material Properties of Armor Components

Steel

Ballistic steel is frequently used for vehicle armor. According to the standardized procedures used to determine material properties as outlined by the American Society for Testing and Materials (ASTM) A370, a typical ballistic steel has high hardness (~500 HBS) but low ductility with only 8% elongation (Steel Warehouse Plate, 2013). This results in good protection against penetration, but can result in fragmentation and spalling of the opposite side of the plate. The steel considered here is DH-36 and is classified by the American Bureau of Shipping (ABS) as a higher strength carbon steel used for shipbuilding that offers improved fracture resistance to impact loadings (American Bureau of Shipping, 2012). DH-36 is more ductile than most traditional armor steels with 21% elongation (BEBON International, 2013). This characteristic results in a fracture resistance greater than most armor steels (Xue et al., 2010). This type of steel exhibits good strength and toughness, very good weldability, and reasonable cost. DH-36 is specified in ASTM A131 to have a minimum yield strength of 355 MPa.

DH-36 was found to have (Klepaczko et al., 2009; Nemet-Nasser et al., 2003) a Poisson ratio of 0.3, a Young's modulus of 210 GPa, a density of 7.8g/cm³, and a chemical composition as shown in Table 1.

Table 1: DH-36 Steel Alloy Composition in %

C max	Si max	Mn	P max	S max	Ti max
0.18	0.5	0.90-1.60	0.035	0.035	0.02
Cu max	Cr max	Ni max	Mo max	Nb	V
0.35	0.2	0.4	0.08	0.02-0.05	0.05-0.10

PSM4

PSM4 is a photoelastic polymer frequently used for stress field visualization. In the following experiments its birefringence is not utilized. This polymer has a relatively low Young's modulus and experiences essentially no plastic deformation or hysteresis even during large strain deformation. This is considered a benefit that permits repeated testing. The material exhibited very little rate dependence. PSM4 is utilized as a model elastic material for comparison with polyurea. It was produced by Vishay Precision Group was stated by the manufacturer to have the following characteristics: a Young's modulus of 3.45MPa, a Poisson ratio of nearly 0.5, and a density of 1 g/cm³. Initial material characterization was completed by uniaxial compression of an upright cylinder and is shown in Figure 3.

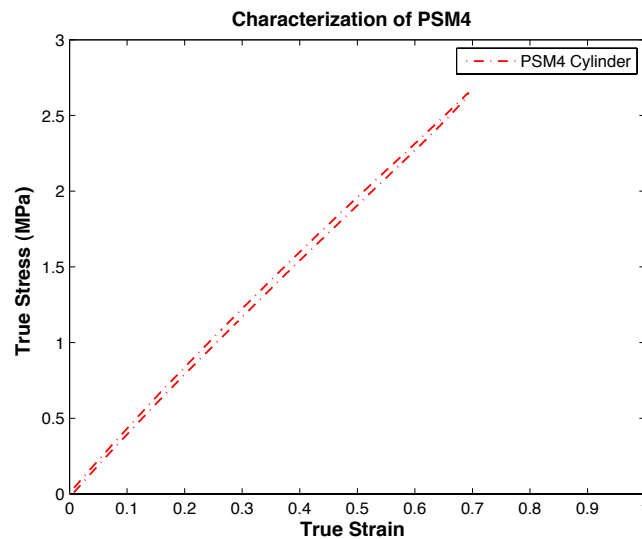


Figure 3: PSM4 stress-strain behavior showing highly elastic large strain behavior

Polyurea

Polyurea is primarily used as a waterproof coating for vehicles, boats, and buildings. Here, polyurea refers to a specific formulation designated as polyurea 1000 (PU). This polymer exhibits large dissipation and resilience with significant rate dependence. The material's stiffening at high strain rates makes it ideal for armor applications. The uniaxial compressive stress-strain behavior of polyurea was examined over 7 decades of strain rate by Sarva et al. Figure 4 shows the behavior of polyurea at strain rates ranging from 10^{-3}s^{-1} to 9000s^{-1} (Sarva et al., 2007).

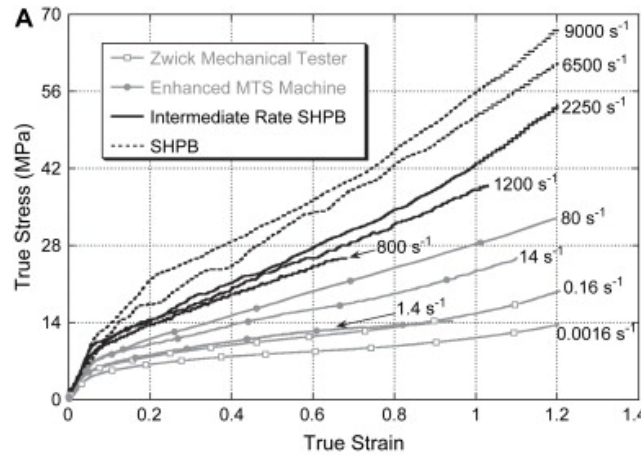


Figure 4: Strain rate stiffening of polyurea reprinted with permission

Chemically, PU is a cross-linked elastomer consisting of hard and soft segments. The “hard” component is diisocyanate and exists in the glassy state at room temperature. The “soft” component is diamine and it exists in the rubbery state at room temperature. The thermodynamic incompatibility results in a phase-separated microstructure (Mock et al., 2011). The large dissipation exhibited under loading, occurs due to a change in the microstructure of the polyurea. Specifically, a breakdown in the hard domain aggregate network structure occurs and is the governing mechanism for the large dissipation of the first loading cycle (Rinaldi et al., 2011). The large dissipation can be seen in Figure 5.

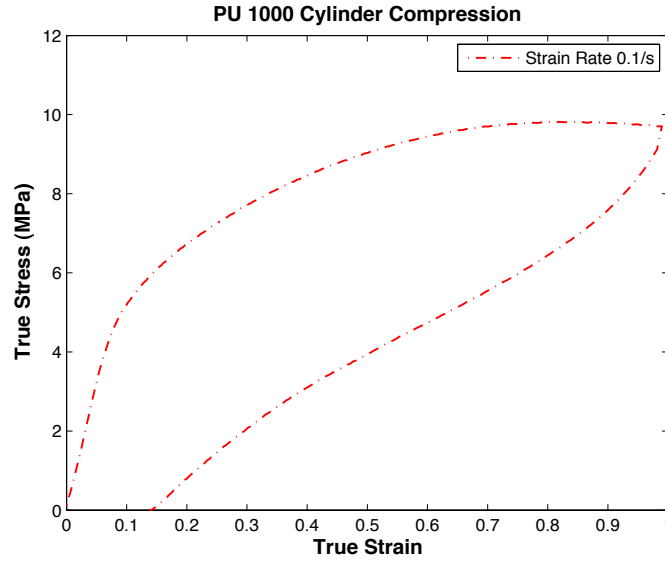


Figure 5: PU 1000 stress-strain behavior showing energy storage and dissipation

The PU used for experimental testing was produced at Naval Surface Warfare Center Carderock Division (NSWCCD). It was created by combining 80% oligomeric amine and 20% of an isocyanate curative (Mock et al., 2011). It is composed of 36% of “hard” isocyanate, which is bulky, stiff, and has a high glass transition temperature. The remainder is “soft” diamine, which is long, flexible, and has a low glass transition temperature. Rinaldi et al used dynamic mechanical analysis (DMA) to show that PU has two glass transition temperatures and exhibits elastomeric-like behavior at room temperature (Rinaldi et al., 2011).

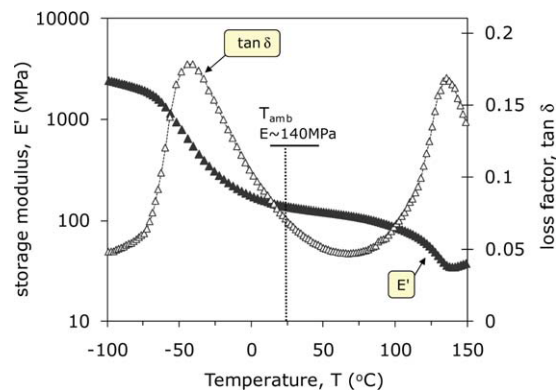


Figure 6: DMA (1 Hz) Isochronal plots of PU between -100 and 150 °C reprinted with permission

The initial Young’s modulus of the PU was determined to be 70 MPa with a density of approximately 1.1 g/cm³.

Material Models of Armor Components

Steel

The deformation characteristics of steel have been well studied and were not reproduced. The properties of the steel used in armor simulations were taken from experiments found in the literature (Dikshit et al., 1995; Klepaczko et al., 2009; Nemat-Nasser et al., 2003). DH-36 is a high strength, low carbon alloy steel. The ASTM defines DH-36 to have a yield strength of 355MPa and an elongation of 21%. The flow stress of the DH-36 was determined using a Johnson-Cook constitutive model with strain rate dependence. Johnson-Cook is a phenomenological model that is matched to experimental data for accurate predictions. The material flow stress is calculated using strain, strain rate, and temperature. The first part of the equation is a hardening relationship that follows the power law where the constant A represents the quasi-static yield stress at the reference strain rate. The constant B provides the strain hardening modulus, while n is the strain-hardening exponent. The second term accounts for the strain rate sensitivity of the material through the constant C. The third term takes in temperature effects. The constant m is temperature sensitivity, T is the current temperature, T₀ is the initial temperatures and T_m is the melting temperature (Klepaczko et al., 2009).

$$\sigma_y = (A + B\varepsilon_p^n)(1 + C \ln(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_o}))(1 - \hat{T}^m) \quad (3)$$

$$\hat{T} = \frac{(T - T_0)}{(T_m - T_0)} \quad (4)$$

Table 2: DH-36 Johnson-Cook Model Parameters

A(MPa)	B(MPa)	n	$\dot{\varepsilon}_o(s^{-1})$	C	m	T _o (K)	T _m (K)
1020	1530	.4	.1	.015	.32	50	1773

Where the metals flow stress, σ_y , is given by material constants, A,B,C,n,m, with reference temperatures T_o, and T_m.

PSM4

PSM4 is a simple polymeric material that provides a basis of analysis to convey the fundamental nature of elasticity and deformation. The study of PSM4 provides an introduction of the mathematical models used in finite element simulations. This material also demonstrates some of the basic response of the more complicated PU polymer used later.

This same material was used by Bertoldi et al to analyze the compression characteristics of PSM4 sheets with a lattice of holes (Bertoldi et al., 2008). They used a second order Yeoh model in order to better capture small strains, which are not as important in this analysis. In this study, strains of 0.2 and higher are common. They found the initial Young's modulus as 3.25 MPa. In contrast, this study used a compressible Neo Hookean model that captures the majority of the moderate and large strains very well. The PSM4 experiments were accurately modeled with ABAQUS 6.11 using the material parameters of 4.35MPa as the initial Young's modulus.

A strain energy density function is used to approximate the mechanical behavior of the material. A compressible model give close results for uniaxial compression up to 0.8 strain. Only the compressible Neo Hookean model was considered in this analysis. The Neo Hookean model is based solely on the first invariant of the left Cauchy-Green deformation tensor (**B**). The left Cauchy-Green strain tensor is based on the deformation gradient (**F**). Assuming **F** is given in the principle directions, the matrix **B** can be constructed as shown in equation 9.

$$\mathbf{B} \stackrel{\text{def}}{=} \mathbf{F}\mathbf{F}^T = \begin{bmatrix} \lambda_1^2 & 0 & 0 \\ 0 & \lambda_2^2 & 0 \\ 0 & 0 & \lambda_3^2 \end{bmatrix} \quad (5)$$

The first invariant (I_1) is the trace of **B**.

$$\text{tr}(\mathbf{B}) = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (6)$$

The compressible strain energy density function (U) is also based on material properties, E_0 , the initial Young's modulus, and κ , the bulk modulus.

$$C_1 = \frac{\mu}{2} = \frac{E_0}{6} \quad (7)$$

$$D_1 = \frac{\kappa}{2} \quad (8)$$

The strain energy density function used for this model is

$$U_{NH} = 2C_1(J^{-2/3}I_1 - 3) + D_1(J-1)^2 \quad (9)$$

The volume ratio J is defined as the determinant of $\mathbf{F}$.

$$J \stackrel{\text{def}}{=} \det(\mathbf{F}) = \lambda_1 \lambda_2 \lambda_3 \quad (10)$$

Considering uniaxial compression in the 1-direction with symmetry

$$\lambda_2 = \lambda_3 = \sqrt{\frac{J}{\lambda}} \quad (11)$$

The relationship between the Cauchy stress and the left Cauchy-Green strain tensor is shown below: (Ogden, 1984)

$$\boldsymbol{\sigma} = \frac{2}{J} \mathbf{B} \frac{\partial U}{\partial \mathbf{B}} \quad (12)$$

The Cauchy stress is found for a general energy density function after differentiation as:

$$\boldsymbol{\sigma} = \frac{2}{J} \left[\left(\frac{\partial U}{\partial I_1} + I_1 \frac{\partial U}{\partial I_2} \right) \mathbf{B} - \frac{\partial U}{\partial I_2} \mathbf{B} \cdot \mathbf{B} \right] + 2J \frac{\partial U}{\partial I_3} \mathbf{1} \quad (13)$$

Where

$$\mathbf{1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (14)$$

After completing the differentiation on the strain energy density function and making use of the uniaxial symmetry, equation 17 is solved for the uniaxial case in terms of stretch and material parameters as

$$\sigma_{11NH} = \frac{4C_1}{3J^{5/3}} \left(\lambda^2 - \frac{J}{\lambda} \right) + 2D_1(J-1) \quad (15)$$

The value of J can be found for each value of λ . It is determined from the boundary conditions and the bulk modulus. Two equivalent equations for stress can be found ($\sigma_{22} = \sigma_{33}$) and when set equal to each other yield the next equation.

$$0 = J^{(8/3)}D_1 - J^{(5/3)}D_1 + \frac{JC_1}{3\lambda} - \frac{C_1\lambda^2}{3} \quad (16)$$

The roots of this equation give J and now σ_{11NH} can be solved. The material parameters C_1 and D_1 used to fit the model to the experimental data were 0.725MPa and 1GPa respectively.

Experimental data and the Neo Hookean model shown in equation 15 are compared and shown in Figure 7.

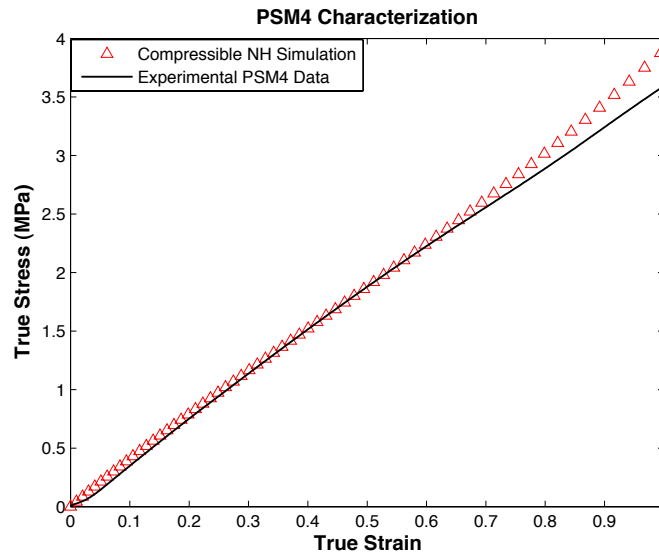


Figure 7: PSM4 experimental and simulated stress-strain using compressible Neo Hookean model

The compressible Neo Hookean model was used in finite element simulations and produced an adequate fit for both uniaxial characterization and constrained cylinder array compression.

Polyurea

PU exhibits a changing response based on its deformation history. It shows both a viscous and an elastic response during loading. As a polymer it is composed of long chains of repeating units. The long chains contain both hard and soft segments in the repeating units. These units can vary in the mixing process and are not necessarily homogeneous. Many of the unique properties of PU occur due to the morphological arrangement of soft and hard segments (Rinaldi et al., 2011).

Viscoelasticity and Viscoplasticity

Viscoelasticity causes PU to creep, to relax, and show rate dependence (Cho et al., 2013). This viscoelasticity also results in hysteresis during loading and unloading. When deformed, PU experiences some plasticity resulting in unrecoverable shape change. This can be most easily seen in the load/unload curve and recognize the

start and finish strains are not equal. PU also undergoes a breakdown in the morphological structure, which softens the behavior and also gives significant hysteresis. The combination of viscoelasticity, viscoplasticity, and strain-induced softening results in an even larger hysteresis than with viscoelasticity alone. The plastic strain of the PU samples is generally 5-20% of the total strain depending on the applied strain. For the maximum strain of 1.0 shown in Figure 8, the permanent plastic strain is about 0.2.

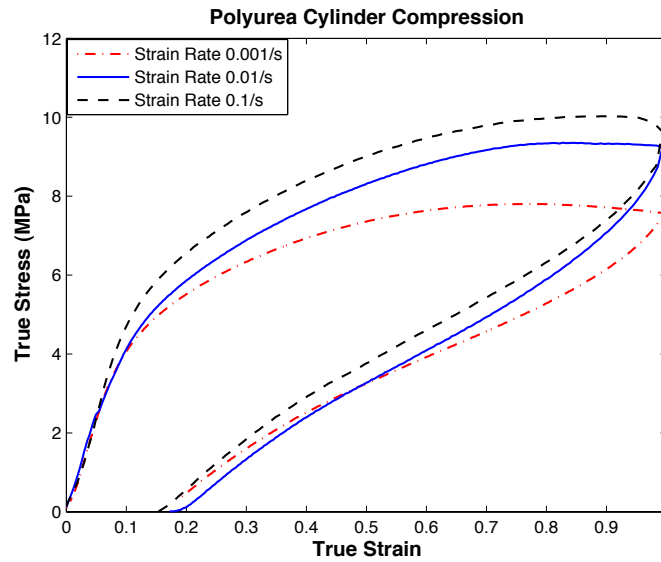


Figure 8: PU Cylinder Compression Is Strain-Rate Dependent

Rate Sensitivity

Small cylinders were tested in compression to determine the loading and unloading characteristics. The hard segments in the polyurea structure govern the low strain rate behavior. As shown in Figure 8, the PU has some rate sensitivity even at these low strain rates. Previous experiments with PU show a substantial jump in strain rate sensitivity around rates of 1/s. Above strain rates of about 1/s, the flow stress of the material increases markedly because the soft segments now offer additional resistance (Cho et al., 2013). At the higher rate, the soft domains are no longer fully above their glass transition temperature and this provides additional resistance to deformation.

Model

Many researchers have attempted to accurately model PU (Shim and Mohr, 2011; Li and Lua, 2009; El Sayed et al., 2009; Amirkhizi, et al., 2006). The loading behavior has a relatively stiff initial response followed by a rollover to a more compliant slope. This type of rollover response has been successfully modeled (Boyce et al., 2000). The unloading response, and related energy dissipation, is more challenging. The model used in this work was developed by Boyce and Cho (Cho et al., 2013) at MIT's Solid Mechanics Lab. The full explanation of the model is found in Soft Matter's 2013 article "Constitutive Modeling of the Rate-Dependent Resilient and Dissipative Large Deformation Behavior of a Segmented Copolymer Polyurea". A brief overview of the constitutive model is given here for general background into its function. The model breaks down the response into 4 general contributions. The hard domain is represented by a spring-dashpot for the intermolecular response and a spring for the network response. The soft domain has a spring-dashpot for the intermolecular response and another spring-dashpot for the network response. The hard network response is best modeled as a compressible Neo Hookean material. The remaining hard intermolecular response is modeled using an elastic element in series with a nonlinear viscous element captured with an Eyring element. The soft intermolecular response again follows a compressible Neo Hookean material and the network response uses an elastic element in series with a nonlinear viscous element.

The constitutive model was implemented through a user-defined material in ABAQUS. The fit of the model with the experimental data for uniaxial compression is shown Figure 9.

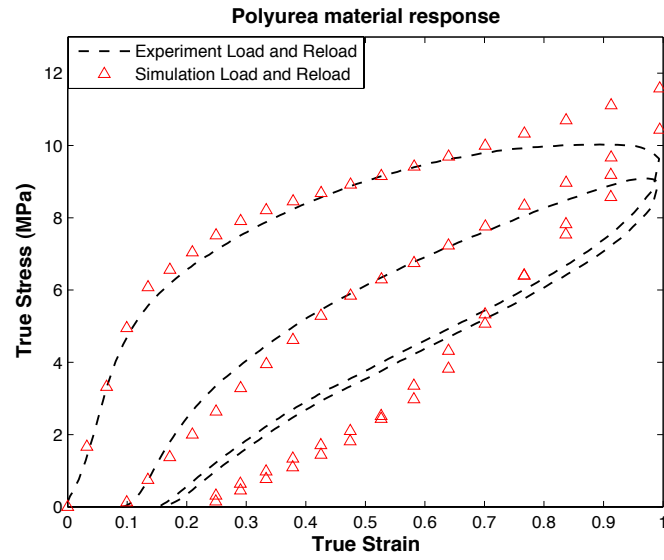


Figure 9: Uniaxial compression using the constitutive model for PU and experimental data at 0.1/s

Chapter 3

PSM4 Array Compression

Materials and Methods

Fabrication and Mechanical Testing

Testing was conducted on 4.8mm diameter PSM4 cylinders measuring 9mm in length. Five cylinders were laid side-by-side with no gap between cylinders and the sidewalls. The cylinder faces were smoothed and lubricated to minimize friction between the face and the fixture. This allowed the plane strain assumption to be used. The array was compressed by a smooth metal bar measuring 24mm long, 9mm wide and 50mm tall. Each array of 1, 2, or 3-rows was considered a unique experiment.

Array Void Fraction

Based on the stacking arrangement, the void volume fraction of the array changes with each layer added.

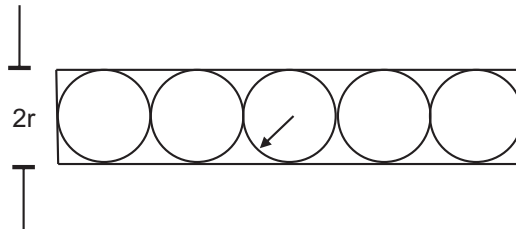


Figure 10: 1-row void dimensions

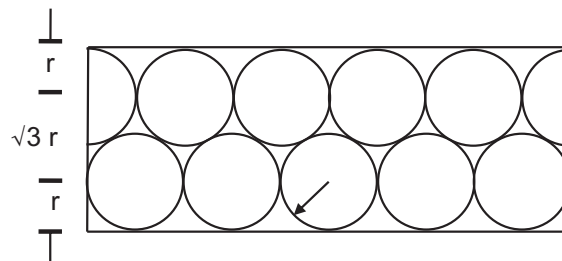


Figure 11: 2-row void dimensions

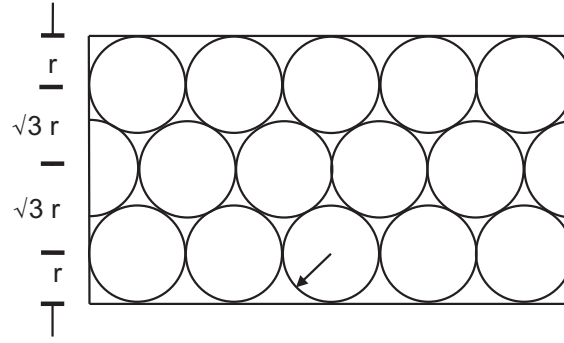


Figure 12: 3-row void dimensions

This is shown graphically in Figure 10 through Figure 12 and is also listed in Table 3. The single row has the greatest initial void fraction because the flat base and compressor do not fill any of the area between the cylinders. The second and subsequent rows fall into the space in the row beneath it resulting in a reduced void fraction. The total height of the 2-row array is $2r + \sqrt{3}r$ or 8.96mm. The height of the 3-row array is $2r + 2\sqrt{3}r$ or 13.11mm. The void fraction continues to decrease as rows are added. Eventually, the impact of the top and bottom rows become insignificant and as the array approaches an infinite number of layers, the void fraction approaches a limit.

$$\text{Initial Void Fraction} = \frac{\text{Total rectangle area} - \text{Cylinder frontal area}}{\text{Total rectangle area}} \quad (17)$$

By letting

$$X = \# \text{ Rows} - 1 \quad (18)$$

The IVF equation becomes

$$\text{IVF} = \frac{10r^2(2+X\sqrt{3})-5(X+1)\pi r^2}{10r^2(2+X\sqrt{3})} \quad (19)$$

or simplified to

$$\text{IVF} = \frac{4-\pi+X(2\sqrt{3}-\pi)}{4+X(2\sqrt{3})} \quad (20)$$

As the number of rows grow (as $X \rightarrow \infty$), the IVF equation approaches a limit.

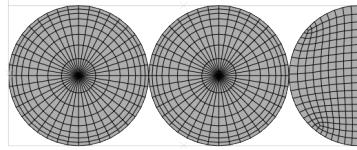
$$\text{IVF} = \frac{2\sqrt{3}-\pi}{2\sqrt{3}} = 0.0931 \quad (21)$$

Table 3: Void Fraction of Various Array Sizes

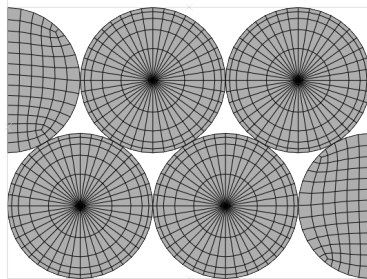
Number	Height (mm)	Initial Void Fraction
1 Row	4.8	0.215
2 Rows	8.96	0.158
3 Rows	13.11	0.138
∞	∞	0.093

Finite Element Model

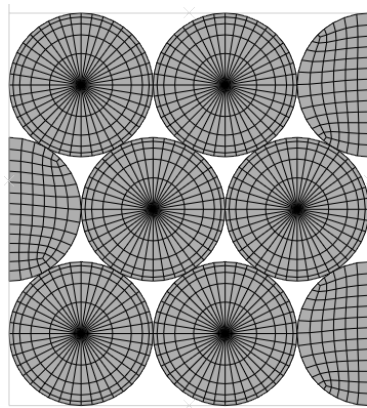
A two-dimensional plane strain model was developed using finite element analysis. The PSM4 cylinders were modeled with 4 node bilinear plane strain quadrilateral elements. The ABAQUS library defines these elements as CPE4R. The cylinders were modeled with contact against rigid sides, top and bottom. The normal contact was defined as “hard”, while the tangential contact was modeled with friction. The coefficient of static friction was 0.1. The mesh can be seen in Figure 13. The model was compressed through displacement control and the reaction force was measured.



1 Row mesh



2 Row mesh



3 Row mesh

Figure 13: PSM4 array finite element models for 1, 2, and 3-rows

Experimental and Simulated Response

Small Cylinder Arrays

In Figure 14, an array with 1-row in the uncompressed state is shown. A speckle pattern was added to the face of the cylinders to allow strain measurement via video extensometer. The array was compressed by $\frac{1}{4}$ of the cylinder diameter, or by 1.2mm for an overall engineering strain of 0.25. The compressed array is shown in Figure 16.

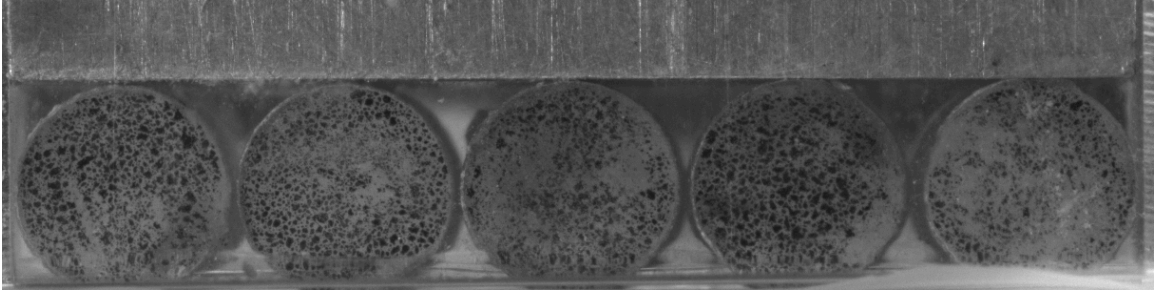


Figure 14: PSM4 array of cylinders shown in uncompressed state

The numerical simulation was carried out with the same sample sizes and boundary conditions as the experiment. The FE simulation is shown in Figure 15 as an overlay on the experimental photo to demonstrate the orientation of the model.

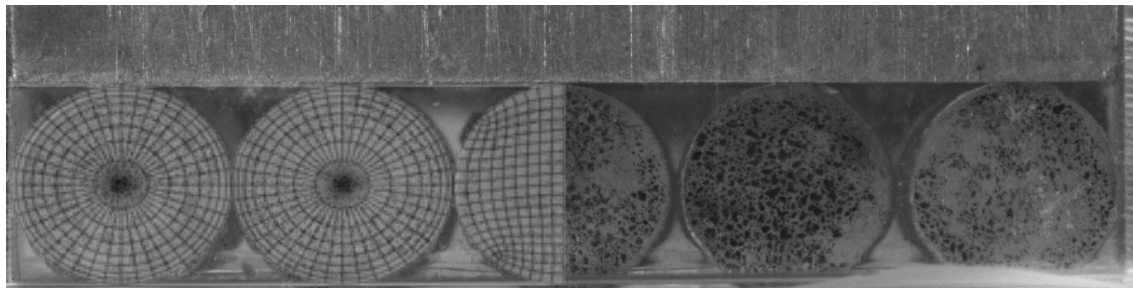


Figure 15: PSM4 array of cylinders uncompressed with FE simulation overlay

The FE model resembled the experiment to the fullest extent possible. In addition to force vs. displacement data shown in Figure 18, the curvature change was also compared with the experimental results.

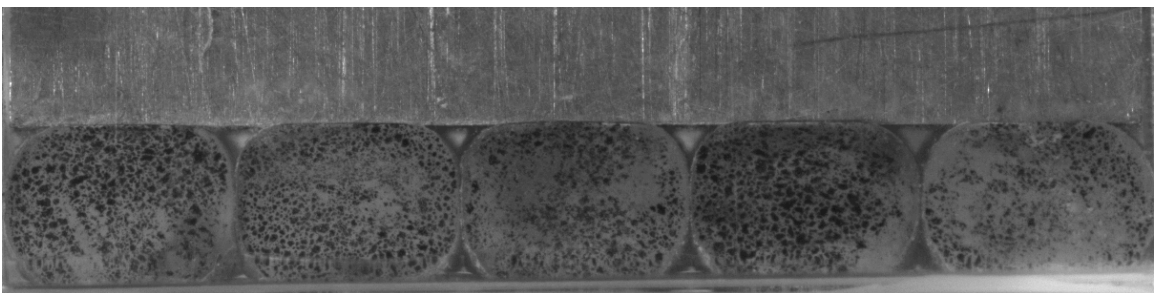


Figure 16: PSM4 array of cylinders in fully compressed state

The array was fully compressed in the finite element model and produced the flattened shapes shown in the shaded portion on the left of Figure 17. While the simulation is close to the experimental results, the simulation slightly overestimates the shape change.

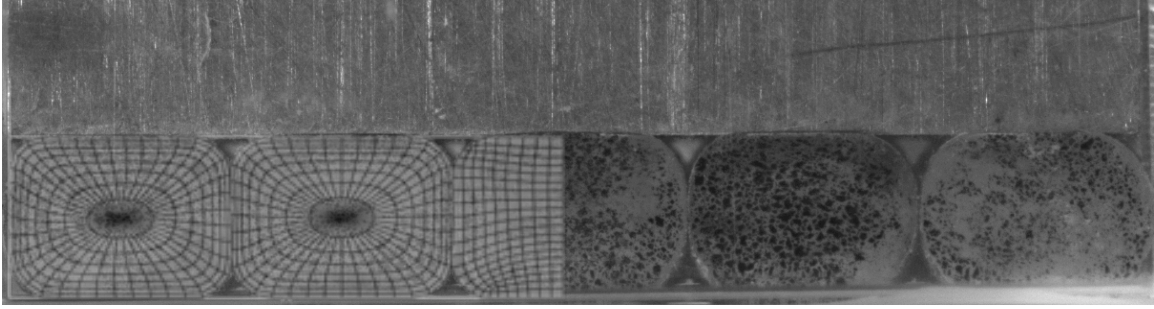


Figure 17: PSM4 array uncompressed state with FE simulation overlay

The experiment was repeated for 1, 2, and 3-rows. Each array was compressed at a constant strain rate of 0.01/s. The force vs. displacement plot with finite element simulation is shown in Figure 18 with very good agreement.

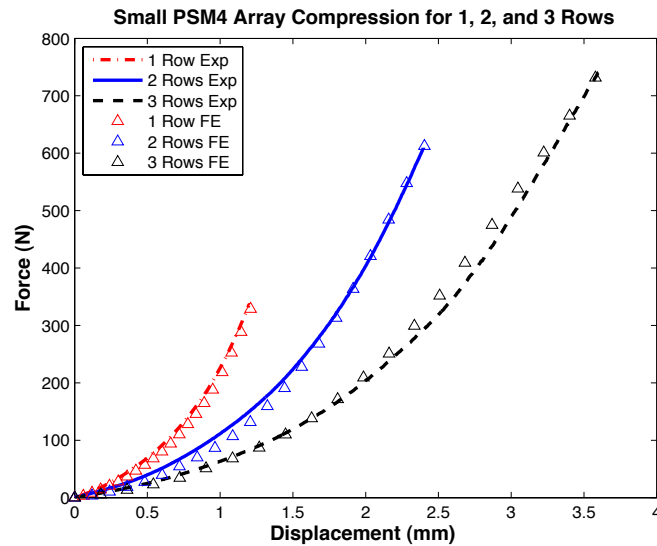


Figure 18: Experimental and simulated data for 1, 2 and 3-rows of PSM4

As more rows are added, the force-displacement response changes and becomes more compliant with the addition of each row, in part, due to the increase in overall height of the sample as each row is added. This dependence on number of rows is not only a height effect but also the void fraction. The effective stress vs. true strain curve is shown in Figure 19. The plots of array compression use effective engineering stress using the initial overall area. The true strain, ϵ , is shown in equation 22.

$$\varepsilon = \ln(\lambda) = \ln\left(\frac{\delta}{H_0}\right) \quad (22)$$

The stress-strain curve shows the 1-row sample to be the most compliant, in part due to the higher void fraction and, in part, due to the manner in which the cylinders deform. The 2-row and 3-row arrays show nearly identical stress-strain behavior due to their similar void fraction and manner in which the cylinders deform. This suggests that the 3-row stress-strain behavior is close to that of an infinite array.

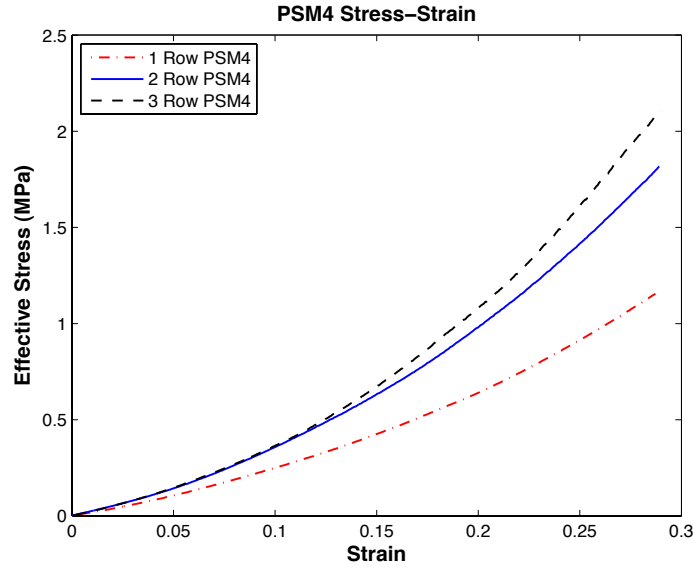


Figure 19: PSM4 array effective stress-strain curve

The experimental strain fields of PSM4 arrays were captured by digital image correlation (DIC). The FE fields for compressive strain, lateral strain, and shear strain are shown for comparison with experiment in Figure 20 through Figure 25.

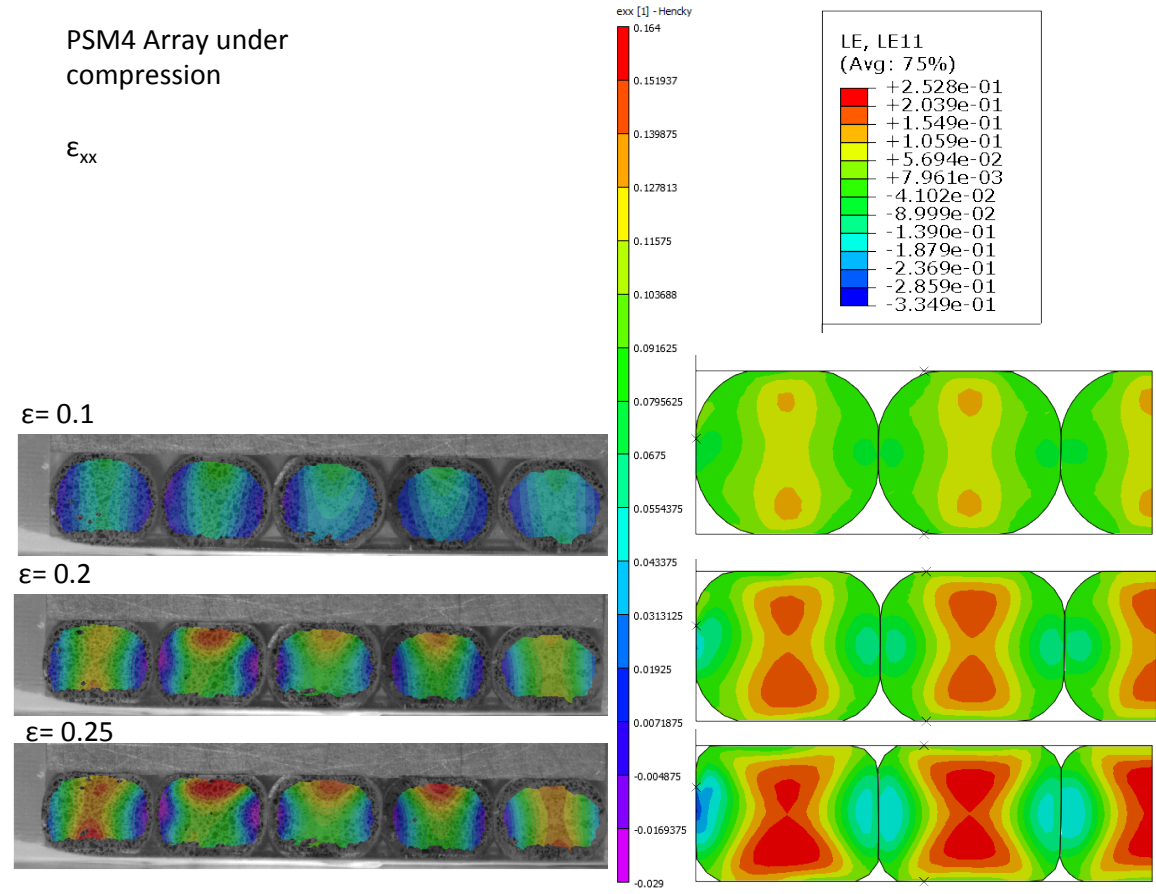


Figure 20: PSM4 1-row array strain field comparison (ϵ_{xx}) of experiment and simulation

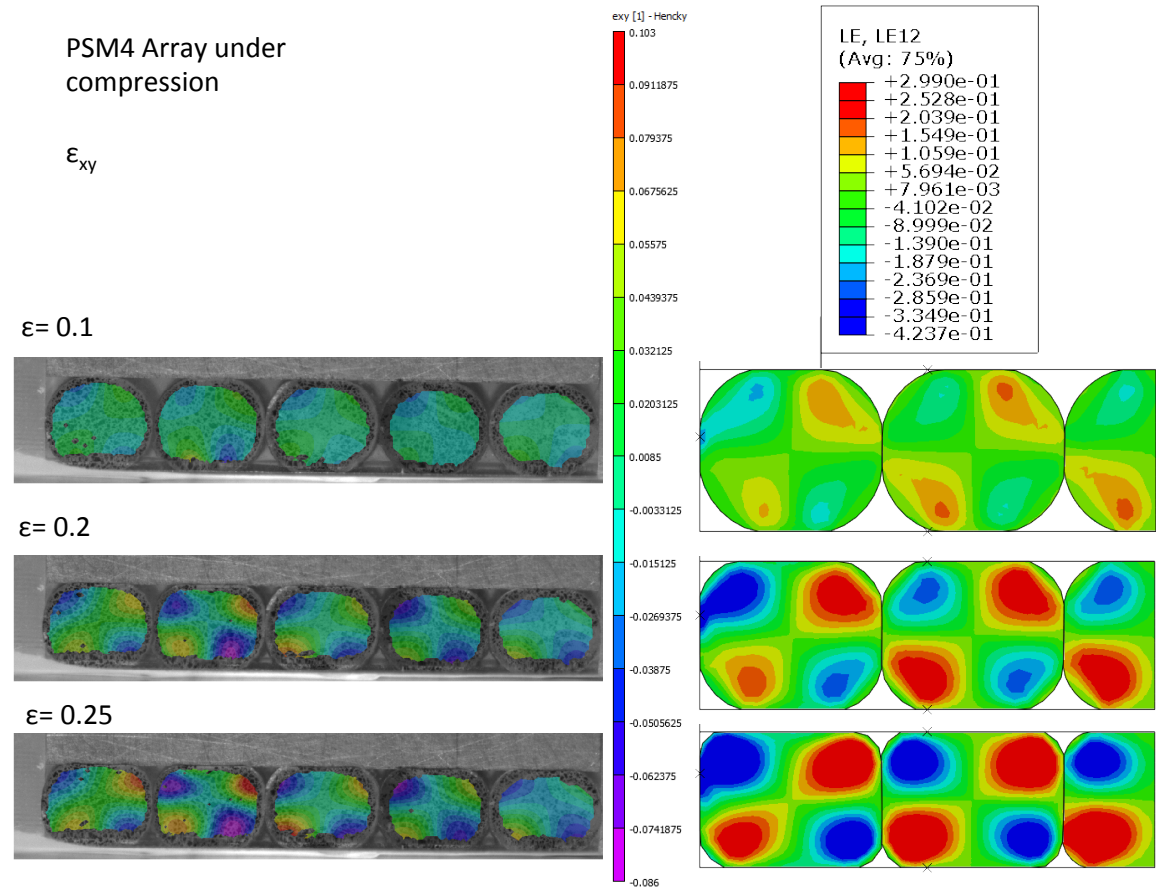


Figure 21: PSM4 1-row array strain field comparison (ϵ_{xy}) of experiment and simulation

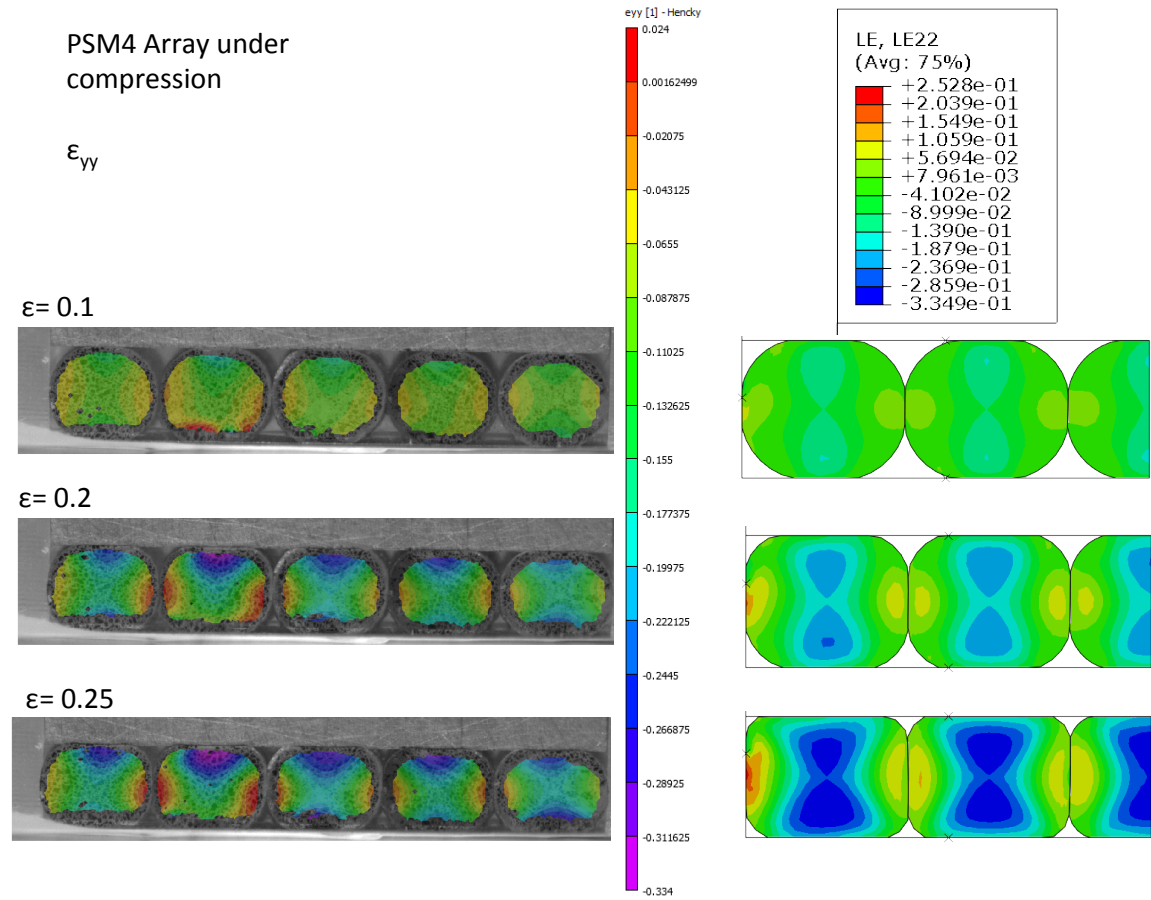


Figure 22: PSM4 1-row array strain field comparison (ϵ_{yy}) of experiment and simulation

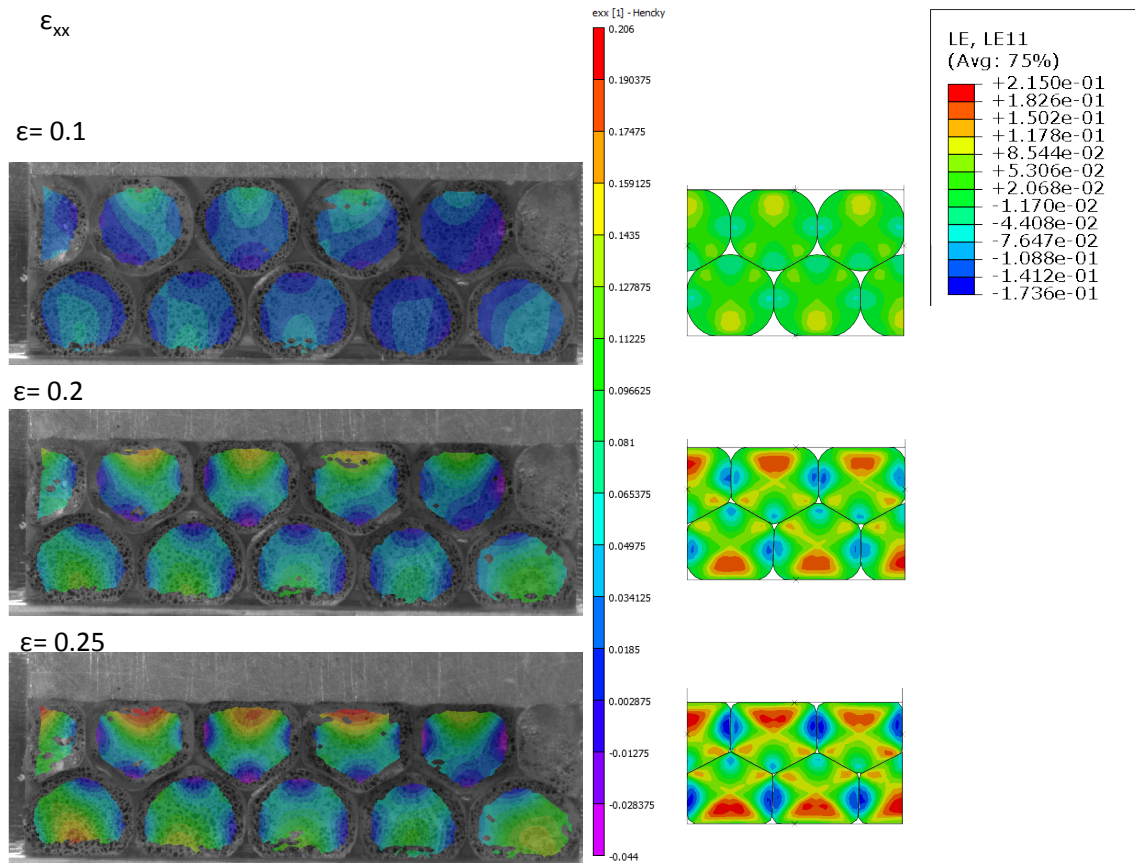


Figure 23: PSM4 2-row array strain field comparison (ϵ_{xx}) of experiment and simulation

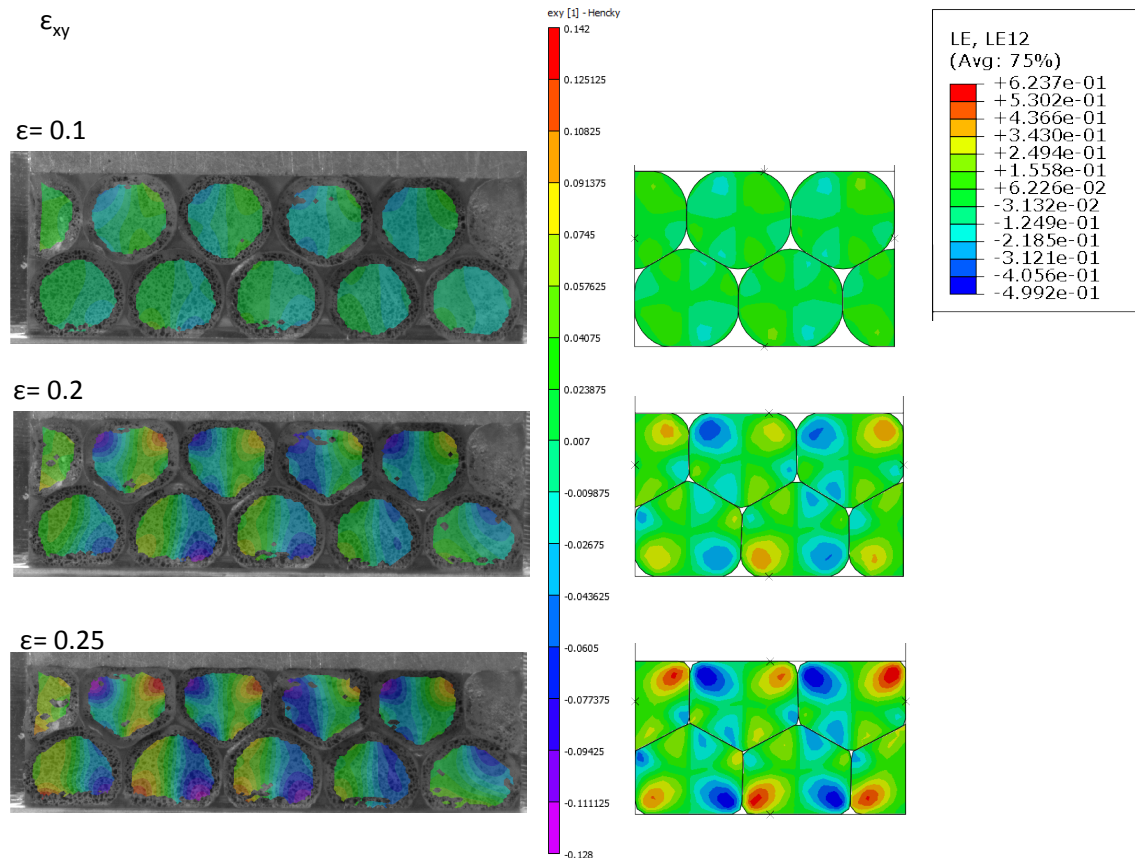


Figure 24: PSM4 2-row array strain field comparison (ϵ_{xy}) of experiment and simulation

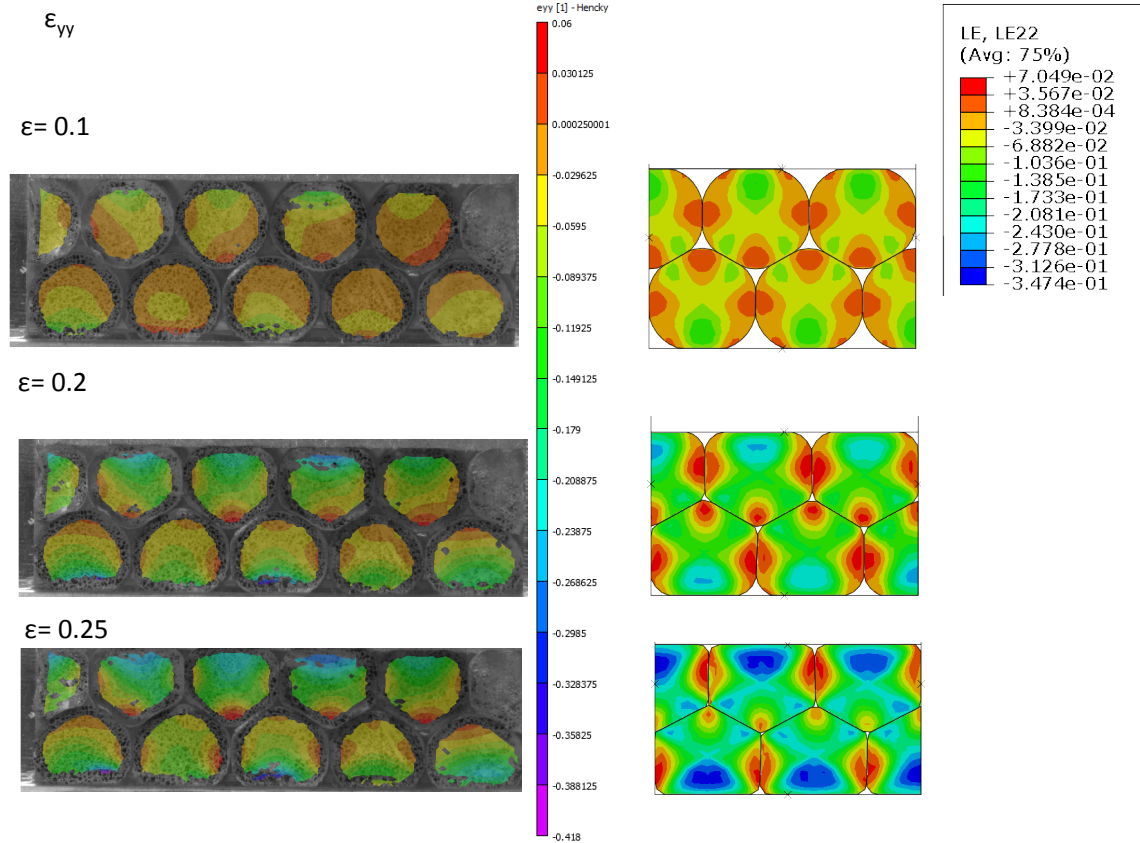


Figure 25: PSM4 2-row array strain field comparison (ϵ_{yy}) of experiment and simulation

Large Cylinder Experiments

In order to validate the small cylinder array results, a larger array was tested. The larger array cylinders were approximately twice the diameter of the small array at 9.2mm and 9.6mm in length. The large cylinders were cut with a laser and did not have tabs like the smaller PSM4 cylinders. The experimental and simulated loading curves shown in Figure 26 show reasonable agreement.

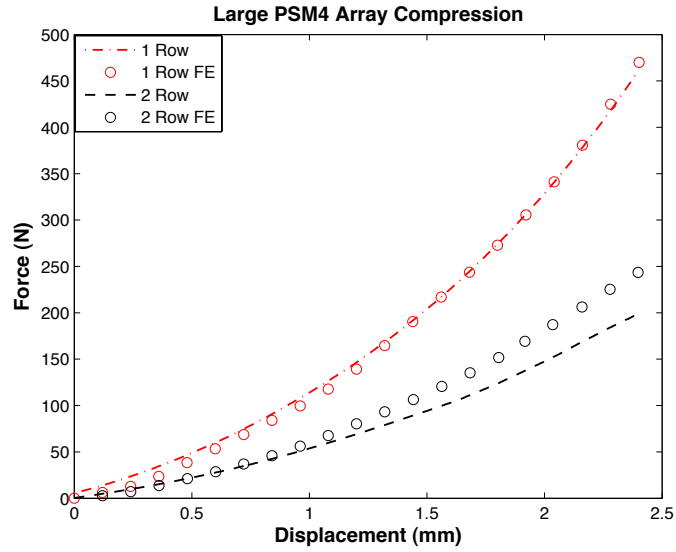


Figure 26: Experimental and simulated data for 1 and 2-rows of large PSM4 cylinders

The finite element simulation produced a force vs. displacement plot that shows good agreement with the 1-row experiment. The array is shown in the uncompressed state in Figure 27 and in the maximum compressed state in Figure 29.

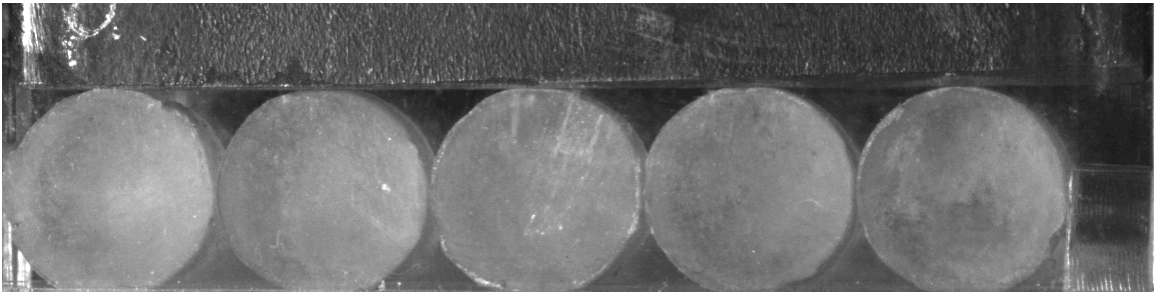


Figure 27: PSM4 large cylinder array--note PMMA spacer on right

The finite element simulation is overlaid on the uncompressed array picture in Figure 28. Only the left half of the array was modeled for computational efficiency. The FE simulation used the experimental sample size and boundary conditions.

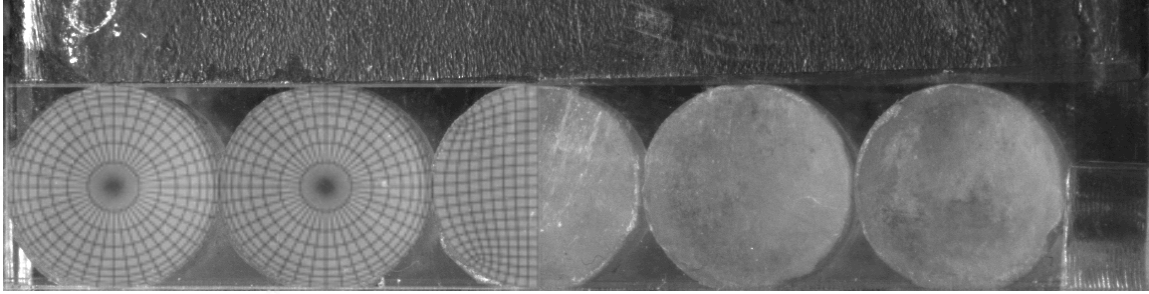


Figure 28: PSM4 large cylinder array uncompressed with FE overlay

The large PSM4 array was compressed to the same maximum strain as the small PSM4 array. A maximum strain of 0.25 was used to capture significant shape change while still enforcing the experimental boundary conditions. The finite element simulation is overlaid on the compressed array picture in Figure 30 with very good agreement.

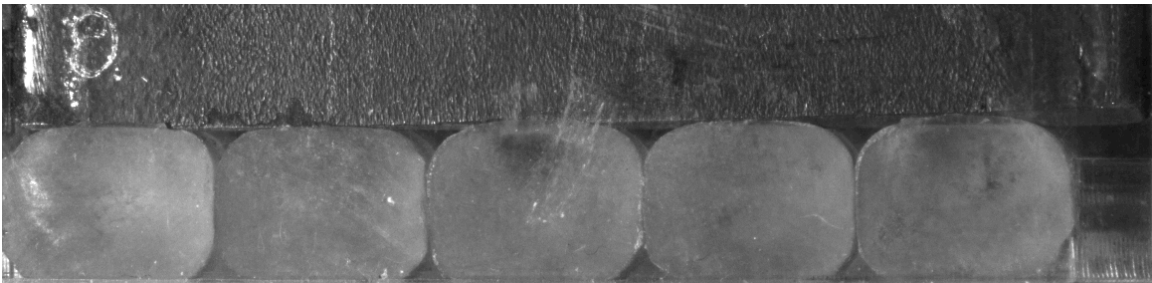


Figure 29: PSM4 large array under full compression

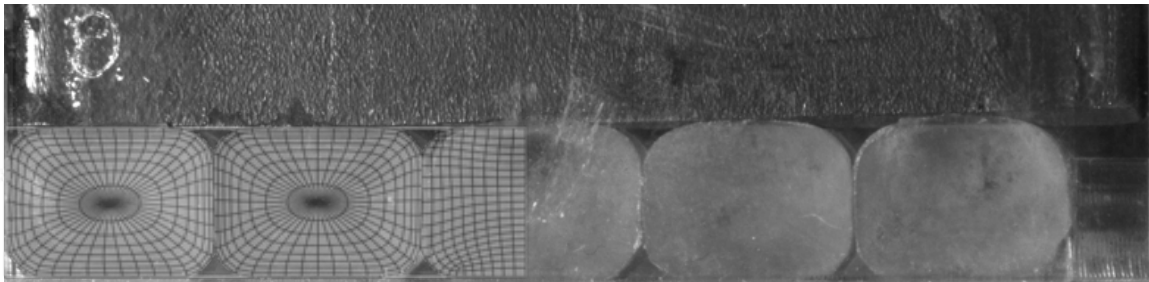


Figure 30: PSM4 large array under full compression with simulated deformed array overlay

Comparison of Large Array and Small Array

The large cylinders were tested to verify that sample fabrication techniques did not affect the experimental results. The force-displacement curves did not match those

of the small array due to the different cylinder dimensions. The large array was compared to the small array using the effective stress of each array vs. the true strain of that array. The effective stress-true strain curves of the large arrays was found and compared to the small arrays. The effective stress was found by taking the force and dividing by the initial overall area of the large array, and the strain was found using the displacement and dividing by the height of the large array. As expected, both the 1 and 2-row large arrays matched the small arrays as shown in Figure 31 below.

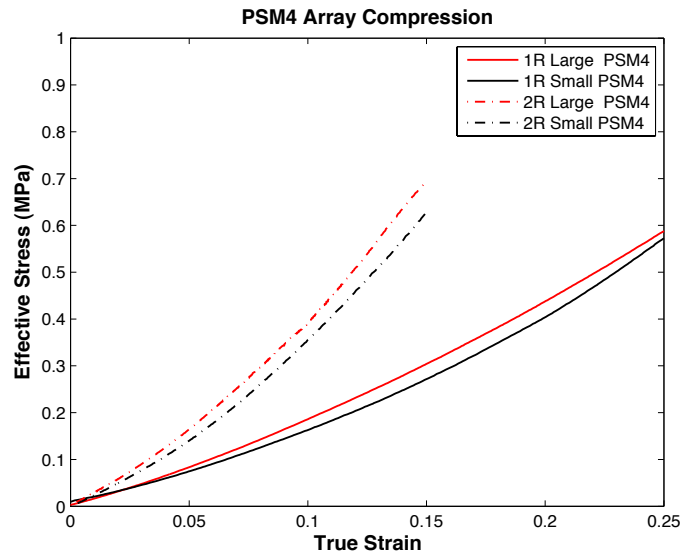


Figure 31: Effective stress-strain comparison of large and small PSM4 arrays

Effects of Lateral Array Constraints

Lateral constraints play a major role in the overall array response. Initially, the array shows a similar compliance with free cylinders under compression as shown in Figure 33. As the material is compressed and the voids are filled, the array responds in a similar fashion to a constrained block of material. This compression regime simply tests the bulk modulus of the material. The initial response of a single row of cylinders can be easily explained. The force that results from one cylinder with no lateral constraint follows simple non-adhesive elastic contact mechanics developed by Hertz as shown below.

$$F=(\pi/4)E^*L\delta \quad (23)$$

Where L is the cylinder length, δ is the indentation depth. The effective Young's modulus (E^*) is found by

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \quad (24)$$

where E_1 and ν_1 are the Young's modulus and Poisson ratio of that material. The effective radius is found by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (25)$$

and the contact radius a, follows

$$a = \sqrt{R\delta} \quad (26)$$

The force was calculated for one cylinder compressed between two plates as shown in Figure 32.

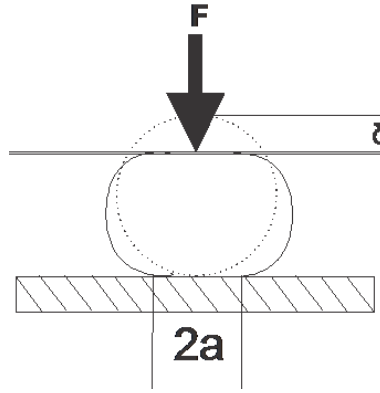


Figure 32: Contact radius resulting from flat plate compression based on Hertz equation for a cylinder

The Hertz contact force for one cylinder was found using the equations above and was multiplied by 5 to simulate the reaction force of the 1-row array when unconstrained laterally. This force was analyzed at several displacements and plotted on Figure 33 as the black (unconstrained) line. As expected, the force, as captured by the Hertz model, initially follows the equation in the small deformation regime. However, at larger deformations, there is an increasing contact area. This changing geometry gives the nonlinear stiffening and departure from the Hertz solution.

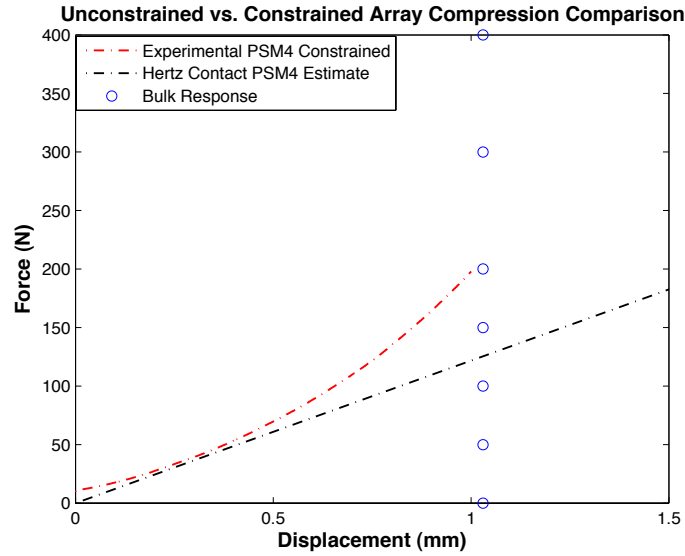


Figure 33: Experimental constrained array vs. unconstrained simulated array using Hertz equation

The other extreme, the fully constrained case, was examined by assuming the cylinders were compressed and fully deformed with horizontal and vertical constraints. The fully constrained and compressed case is shown in Figure 34. Constant volume is assumed during the deformation until the cylinder has become a block. The bulk modulus of the PSM4 material is approximately 2 GPa and results in a nearly vertical line (blue circles) in the force vs. displacement plot. The experimental results show this vertical line is approached, but due to flexing of the compression fixture, a fully constrained condition could not be achieved experimentally.

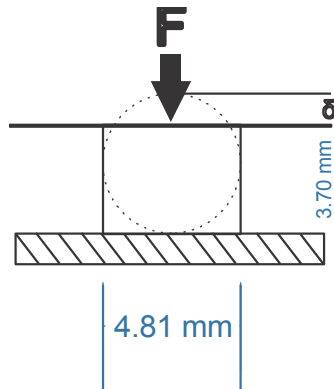


Figure 34: Deformation of fully constrained compression

Effect of Compression on Void Fraction

As the array is compressed, the void fraction changes. The cylinders deform and become more flat with sharper corners. The interstitial area is slowly filled, while the density of the material also increases slightly. The resulting change in the void fraction is shown in the middle plot of Figure 35. Additionally, the instantaneous slope (k) of the force vs. displacement experimental curve was compared with the simulated values in the bottom plot of Figure 35.

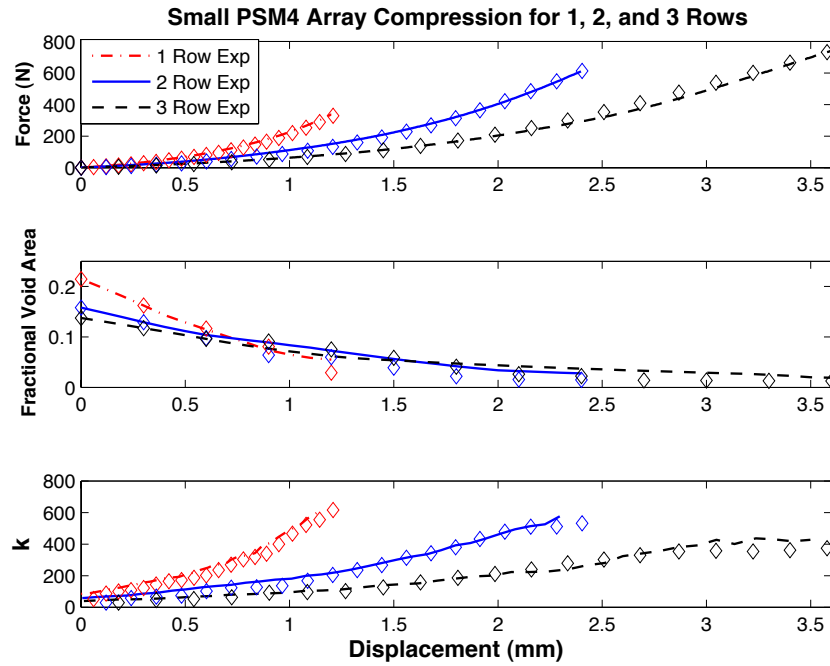


Figure 35: Void and slope change compared with compressive force on 1, 2, and 3-row arrays

The initial void fraction partially governs the response of the array. As shown in the middle plot of Figure 35, the initial void fraction slope of 1-row is much steeper than that of the 2 and 3-rows. The 2 and 3-row void fraction curves are close together indicating they are close to the infinite value. The effective stress vs. strain plot of the PSM4 arrays in Figure 19 shows a significantly more compliant response for 1-row and a nearly identical low strain response for 2 and 3-rows. For a given strain on the array, the stress increases as the initial void fraction is reduced. The slope of the effective stress vs. strain curves continues to increase as the initial void fraction

decreases. Eventually, as the initial void fraction goes to zero, the bulk modulus of the material is tested when the fully constrained material is further compressed.

Conclusions

The preceding experiments demonstrate the impact of a new geometry on the array response. The cylinder array response is based on the material itself, the initial void fraction, and the cylinder contact area. The constrained array response of PSM4 is shown in Figure 36 for 1, 2, and 3-rows. The digital image correlation in Appendix A shows that the 1-row array has the largest contact area with the compression bar and the highest peak local stresses. The single row has the largest initial void fraction, and this results in the greatest compliance.

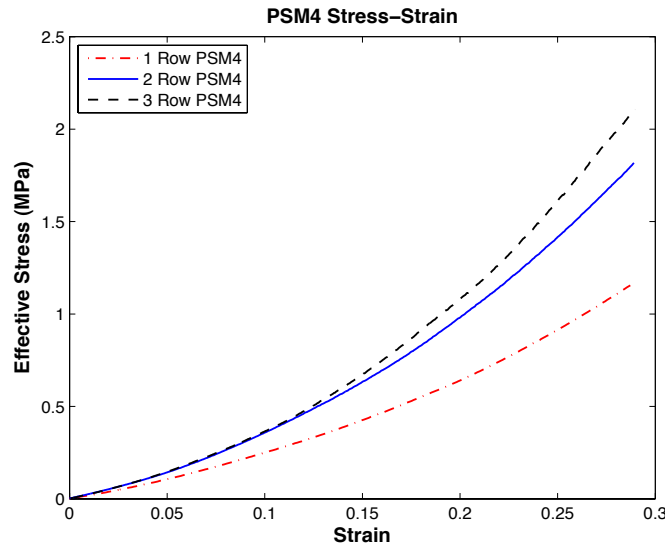


Figure 36: PSM4 experimental effective stress-strain curve

The arrays initially deform almost freely and follow the unconstrained Hertz force for small strains. The initial void volume of the array is reduced as the cylinders deform and take up the interstitial space. The array response rapidly stiffens as the material becomes more fully constrained. This initial compliance and subsequent stiffening can be explained by analyzing the impact of the initial void fraction and the material's constraints. The global tunable stiffness exhibited by the arrays can have many uses.

Geometry can be used to create a unique global response with the same material. One application for this type of response is composite armor. If a constrained polymer is combined with steel, such as in a steel-polymer-steel sandwich, the steel's strength and large energy dissipation during plastic deformation could be used capture the initial event. As the steel continues to deform and weaken, the polymer increasingly stiffens and may limit further deformation of the steel to prevent fracture.

Chapter 4

Polyurea Array Compression

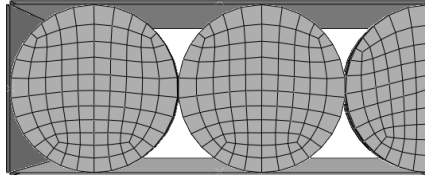
Materials and Methods

Fabrication and Mechanical Testing

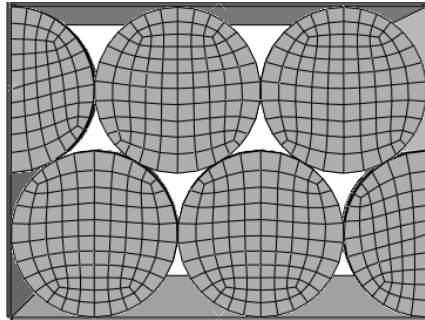
The PU samples obtained from NSWCCD were cut from a solid puck shown in Figure 79 using a water jet cutter. Material characterization was completed by uniaxial compression of upright cylinders. Various height-to-diameter ratios were compared with consistent results. Most samples were 4.8mm in diameter and 4.8mm tall. Several different lubricants were used. A copper nanoparticle deposition provided the most accurate results for the characterization experiments, and calcium bicarbonate gave the best results for array compression. The samples were tested at various strain rates from 0.001/s up to 0.1/s. The material exhibited significant rate dependence as shown in Figure 8. Higher strain rates were tested, but the data collection speed was not adequate for accurate results.

Finite Element Model

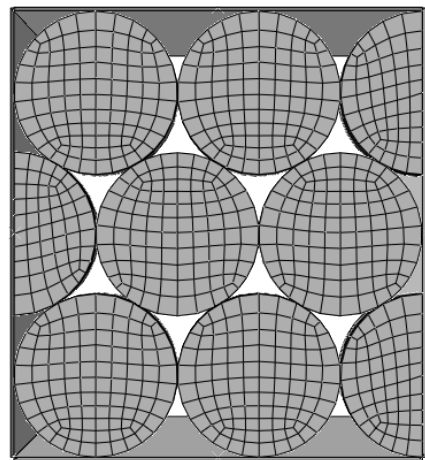
The polyurea model developed by Cho and Boyce was previously explained in Chapter 2 and was used for the numerical analysis with the constrained arrays (Cho et al., 2013). The solid material was discretized into 3d elements with eight nodes and reduced integration defined as C3D8R by the ABAQUS library. The mesh for each row can be seen in Figure 37. The modeled used displacement control and generated loading and unloading curves.



1-Row Mesh



2-Row Mesh



3-Row Mesh

Figure 37: Polyurea array simulation mesh for 1,2, and 3-rows

Experimental and Simulated Response

Small Cylinder Arrays

The same fixture and experimental setup for the PSM4 was used for the PU array testing to ensure plane strain conditions. Each array measured 5 cylinders wide. Each cylinder measured 4.8mm in diameter and 9mm tall. The array was compressed by a smooth metal bar measuring 24mm long, 9mm wide and 50mm tall and shown in Figure 83. The 1-row cylindrical array in the uncompressed state is shown in Figure 38.

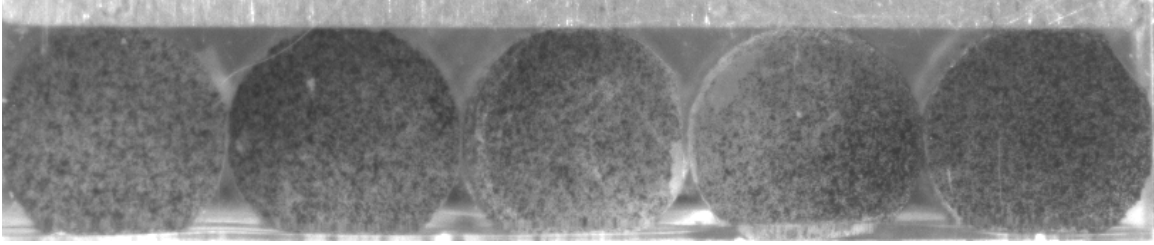


Figure 38: Polyurea cylinder array uncompressed

The FE model used symmetry to reduce the computation time. The uncompressed FE model is overlaid in grey on the left half of the experimental photo in Figure 39.

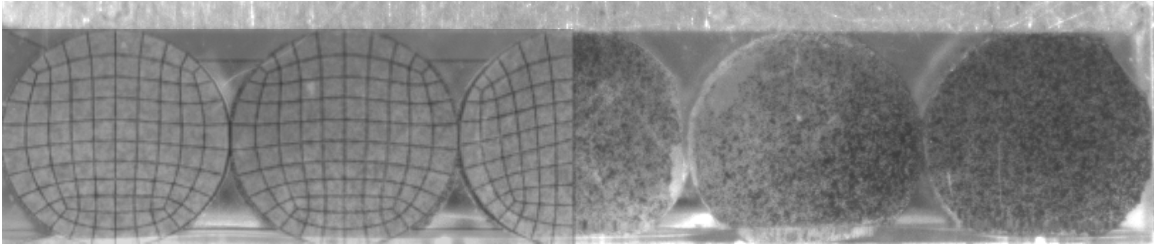


Figure 39: Polyurea cylinder array uncompressed with FE overlay

The array was compressed to various displacements and compared with the FE model force vs. displacement curve and shape change. The shape change can be seen in Figure 40 below. The overlay of the 1-row FE model and the experiment in their fully compressed states is shown in Figure 41 below.

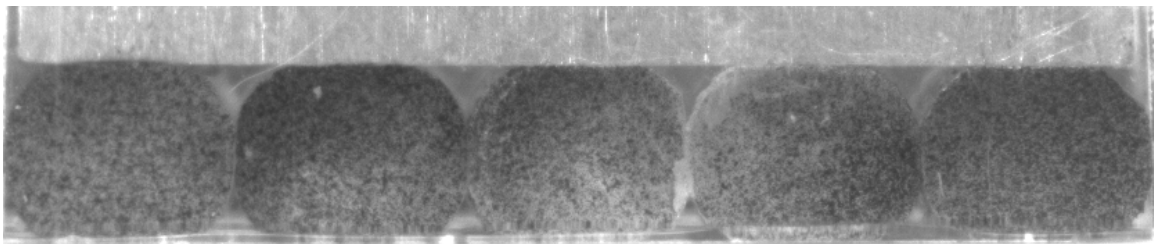


Figure 40: Polyurea cylinder area in the compressed state

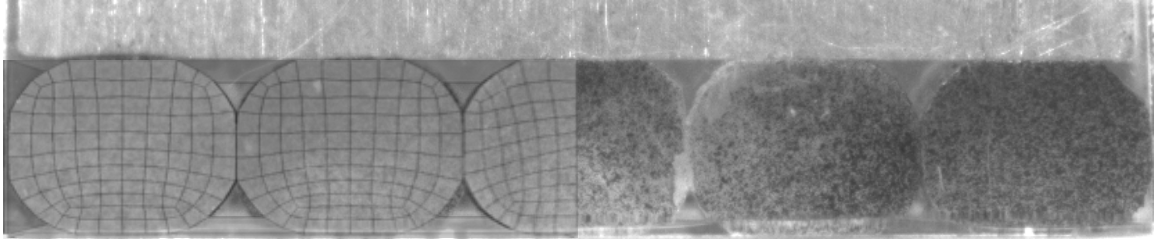


Figure 41: Polyurea cylinder array compressed with FE overlay

The deformed 2 and 3-row arrays are shown in Figure 42 and Figure 43 with FE mesh for comparison. In general, the FE deformation is more severe than the experimental photograph. This is due to the flexibility of the compression fixture and therefore less precise experimental constraints.

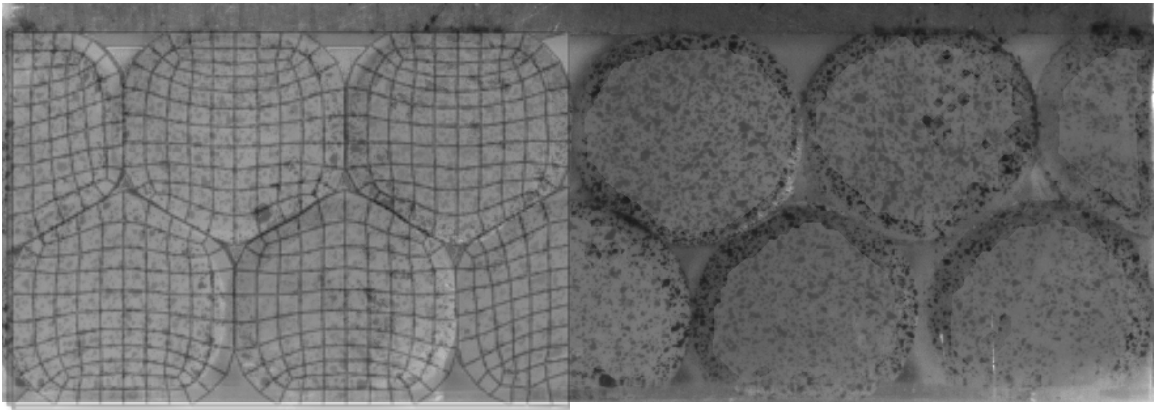


Figure 42: 2-row polyurea array in compressed state with FE overlay

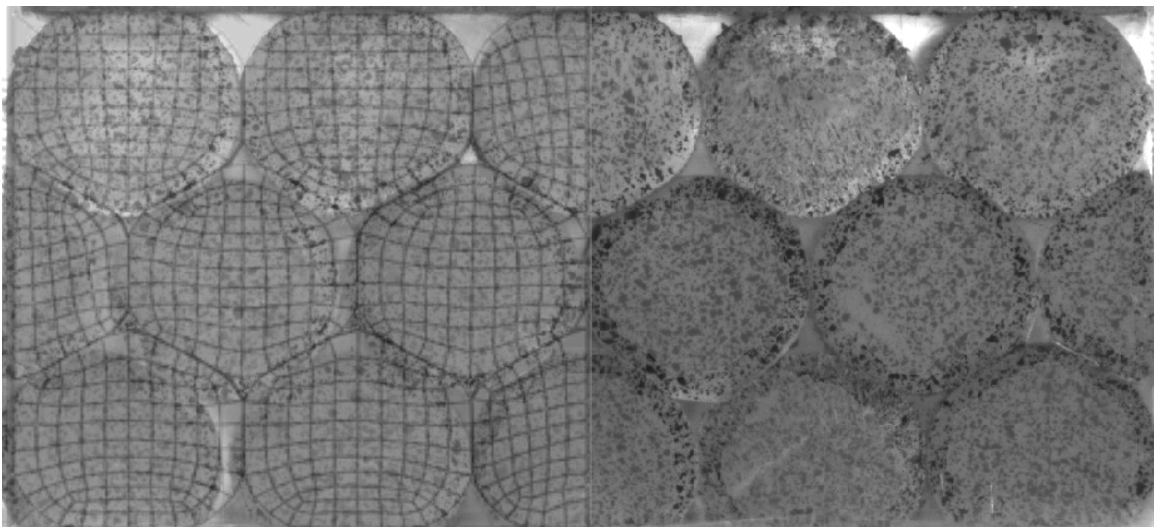


Figure 43: 3-row polyurea array in compressed state with FE overlay

Each array of 1, 2, or 3-rows was considered a unique experiment. Because the microstructure of the PU physically changes under strain, the samples could not be used again for another test. The exception to this was during reloading tests where the permanent dissipation was studied. The constitutive polyurea model developed by the Boyce group and explained in Chapter 2 was used to simulate array compression for 1,2, and 3-row cylindrical arrays. The force vs. displacement plot is shown in Figure 44. A comparison of the ideally constrained FE simulations and experimental results can be seen in Figure 45. The FE data accurately captured the peak loading and unloading behavior. The experimental force was likely reduced by modest bending of the PMMA fixture under higher loads. As seen in Figure 40 above, the polyurea cylinders pushed the front PMMA face out and permitted some expansion of the cylinders through elongation, reducing the peak experimental force. If the cylinders were fully constrained in a stiffer fixture, the peak force would be closer to the FE result.

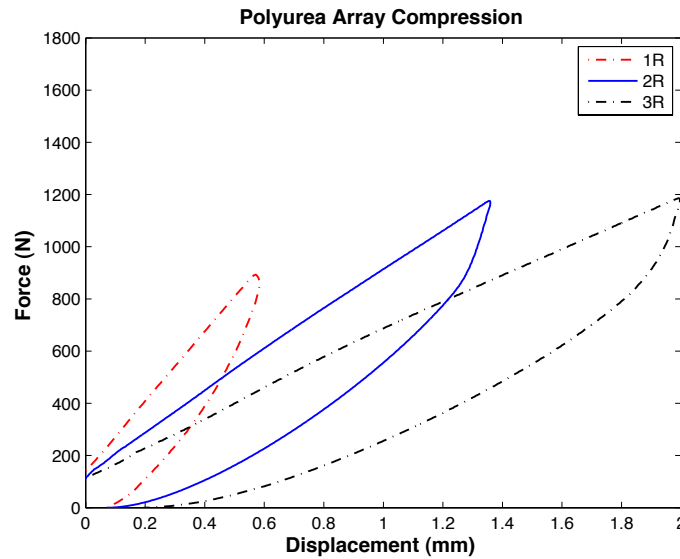


Figure 44: Polyurea array compression experiments

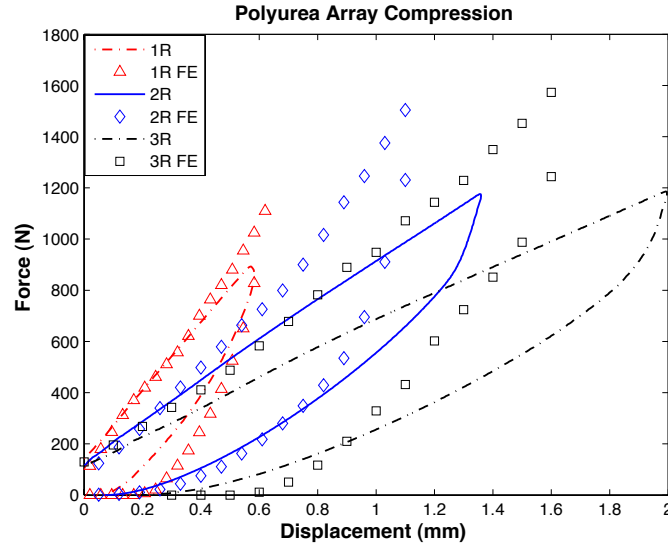


Figure 45: Polyurea array compression experiments with FE simulations

The 1-row experiment and simulation general response match well, with a deviation only a higher forces. The 2 and 3 row experiments are increasingly compliant compared to the simulations. This compliance was primarily caused by an increase in the constrained experimental volume through the elongation of the cylinders. As the cylinders were compressed they created a lateral force stretching the experimental fixture in the horizontal direction and increased the volume of the experiment. The samples also elongated under compression and stretched the face of the fixture in the out-of-the-page direction. This also increased the volume of the samples occupied and further weakened the constant volume goal of the imposed constraints. When the volume increased, the testing of the bulk response became delayed and the compliance of the fixture was tested. For this reason, the experimental tests showed excessive compliance. An additional observation was made regarding the unloading curves, and therefore the dissipation. The simulated unloading curves show more dissipation than the experimental curve due to the reduced peak experimental force and shape change.

A speckle pattern was sprayed on the faces of the cylinders in the array tests. Digital image correlation (DIC) was used to determine the strain field for the various tests.

All the arrays were compressed to a strain of 0.15 at a strain rate of 0.01/s. The true strain fields for the y direction, labeled ϵ_{yy} , and the x direction, ϵ_{xx} , and also the shear strain, ϵ_{xy} can be seen in Figure 47 to Figure 54. Differences between the experimental and simulated strain fields occur due to the bending of the compression fixture. The experimental constraints were not effectively maintained at larger forces resulting in variation from the simulated results. The force vs. displacement experimental data was converted to effective stress vs. true strain as shown in Figure 46. The arrays exhibited dissipation and a unique response based on the number of rows present.

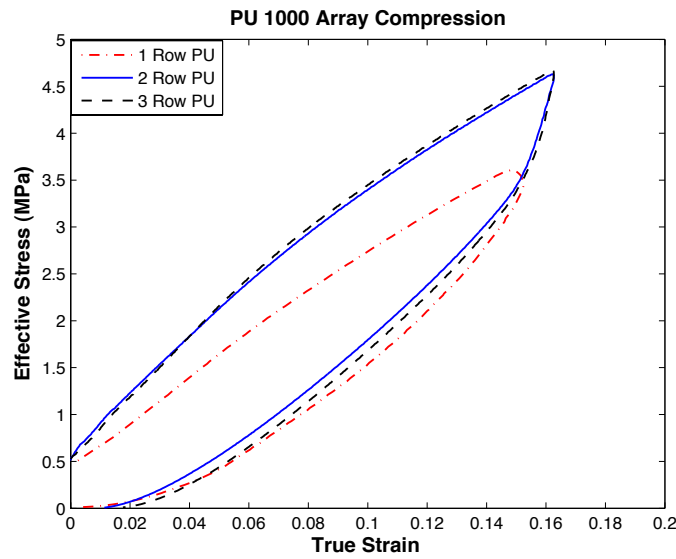


Figure 46: Effective stress-strain curves for PU array compression for 1,2, and 3-rows

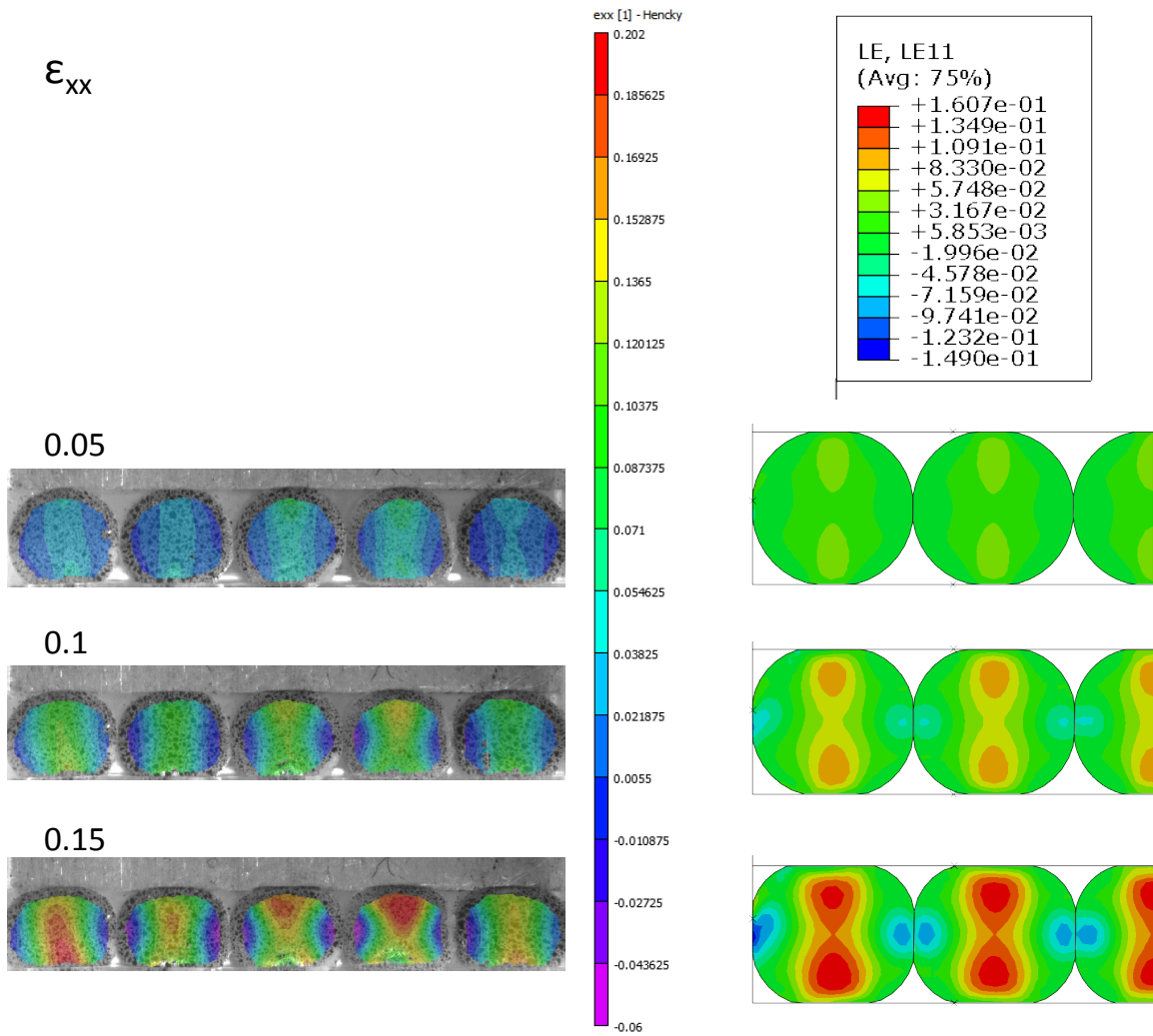


Figure 47: Polyurea 1-row array strain field ϵ_{xx}

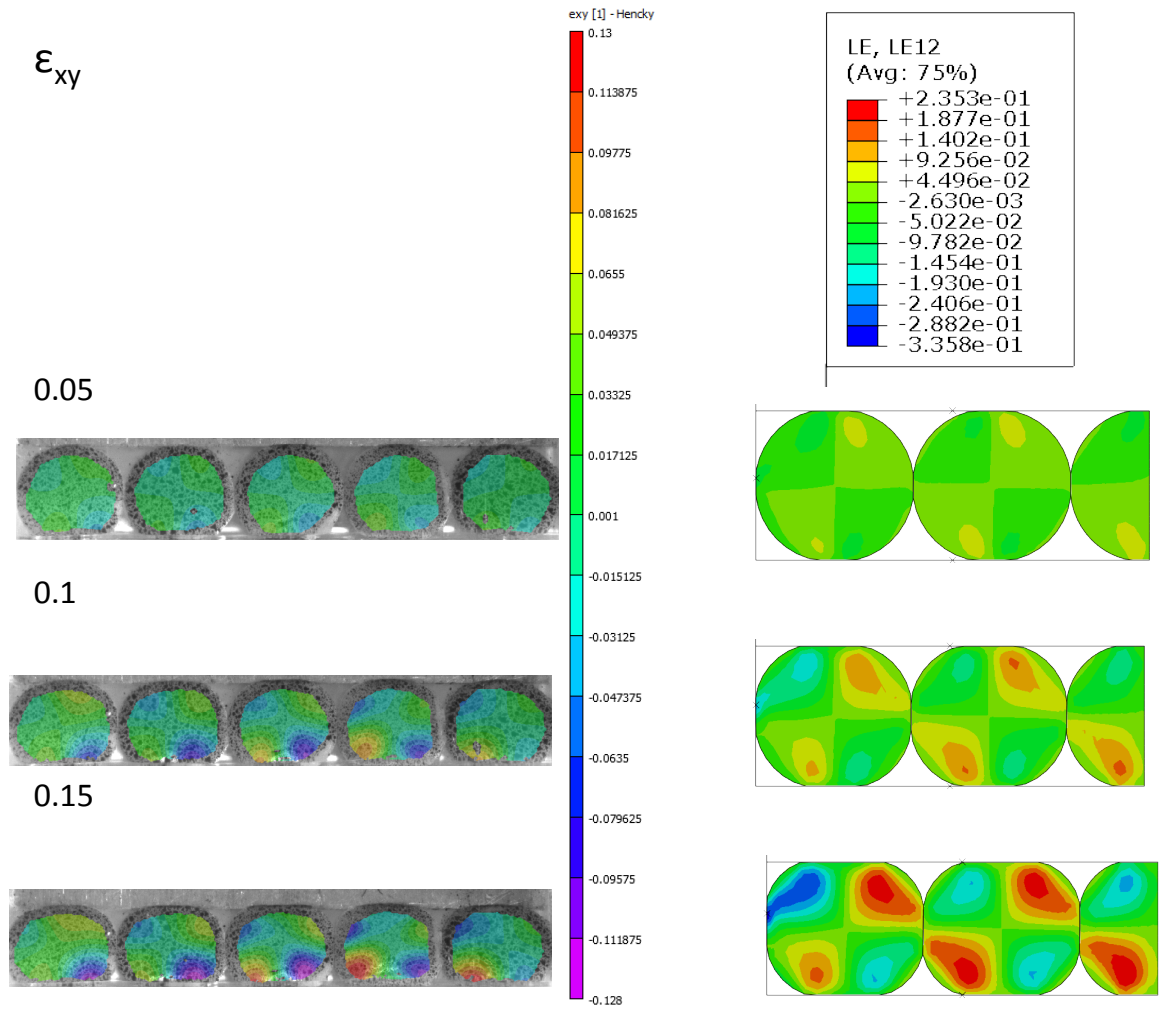


Figure 48: Polyurea 1-row array strain field ϵ_{xy}

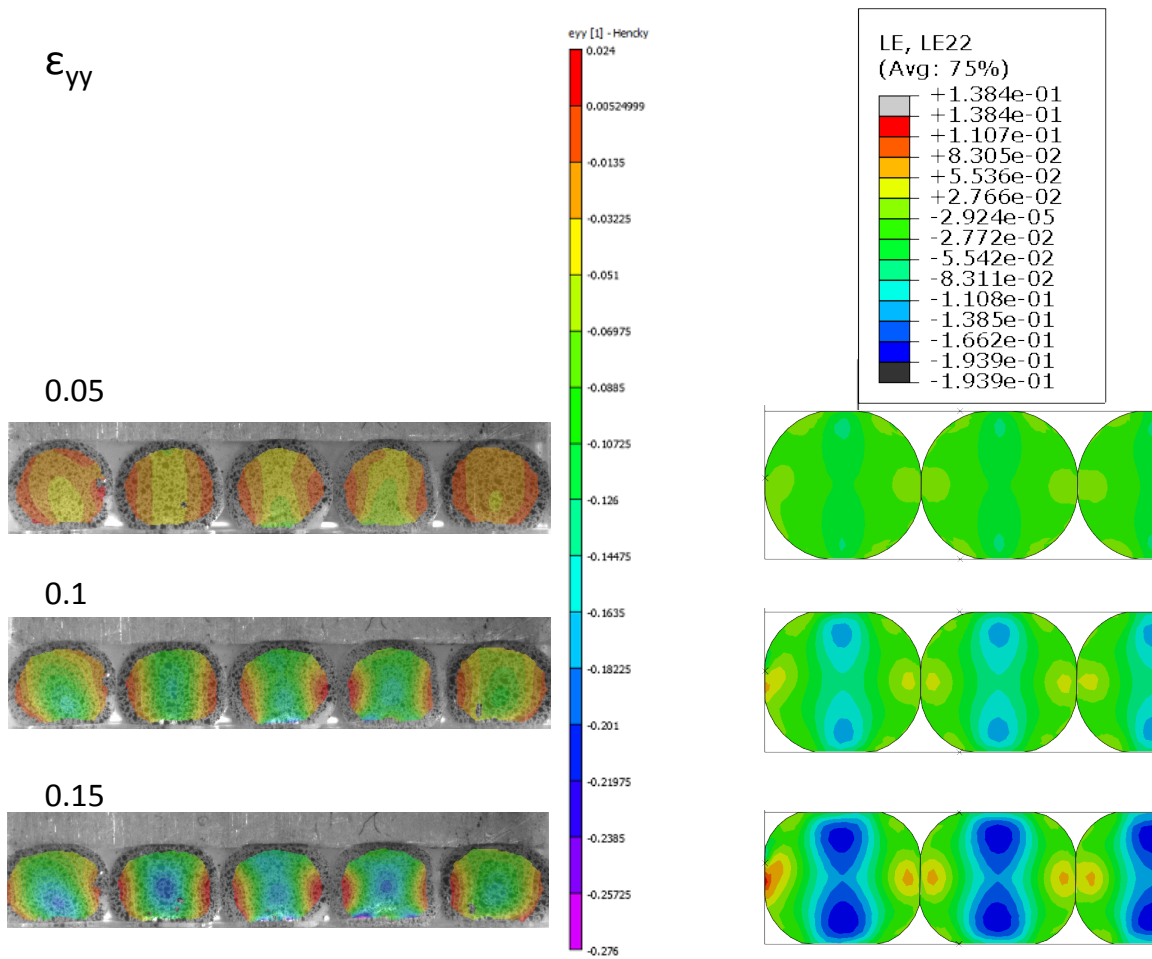


Figure 49: Polyurea 1-row array strain field ϵ_{yy}

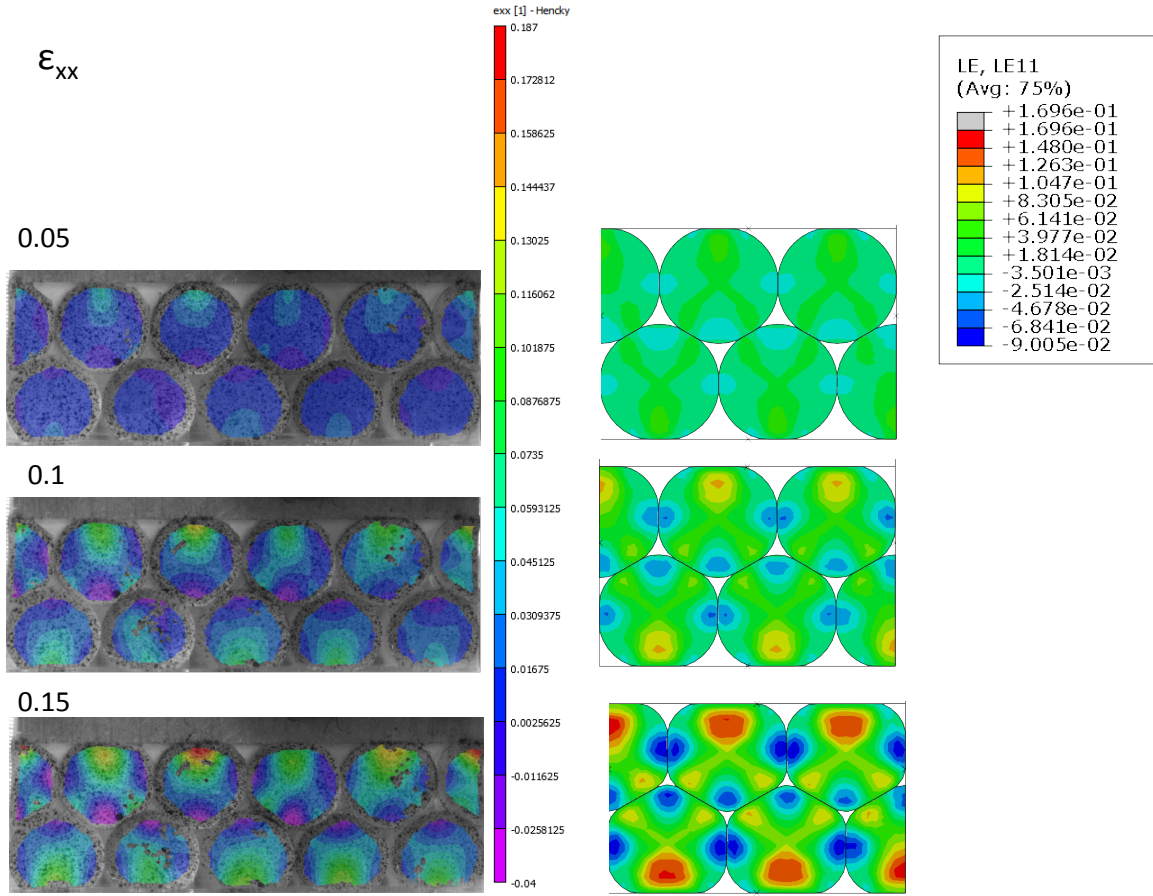


Figure 50: Polyurea 2-row array strain field ϵ_{xx}

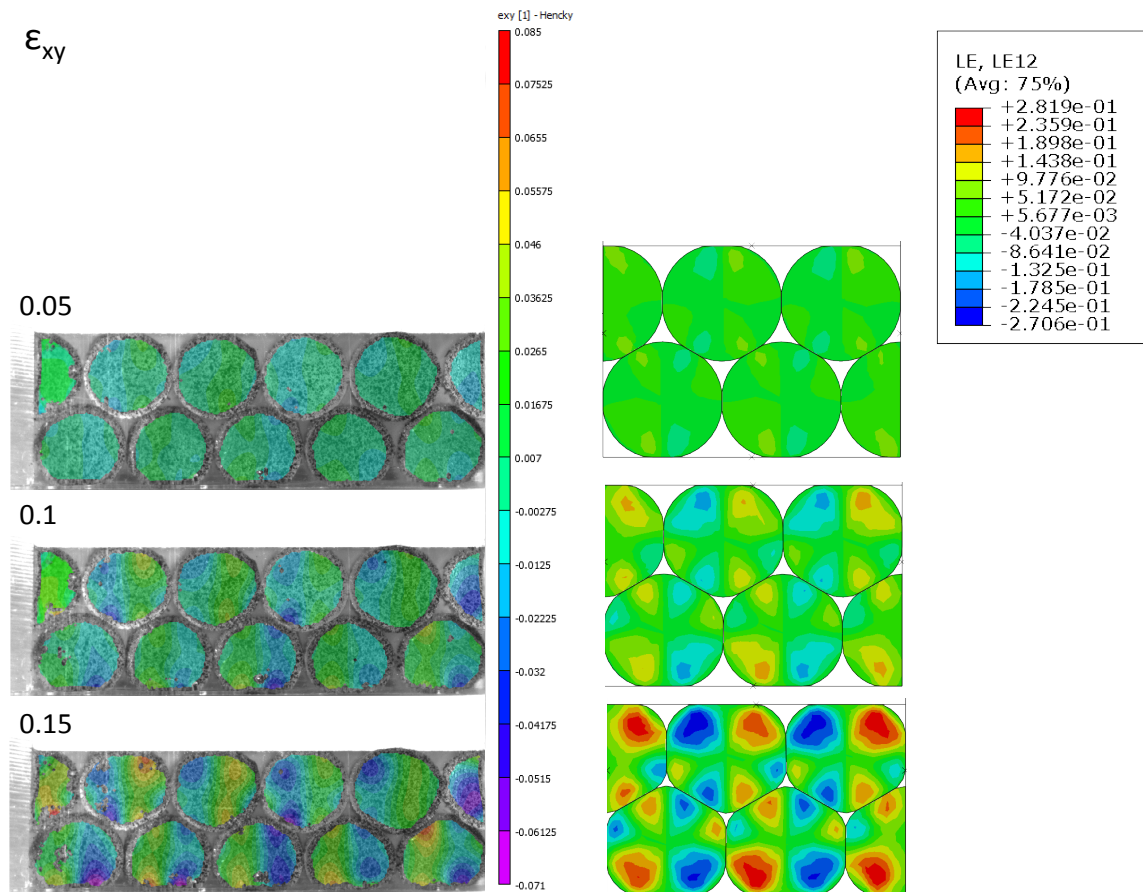


Figure 51: Polyurea 2-row array strain field ϵ_{xy}

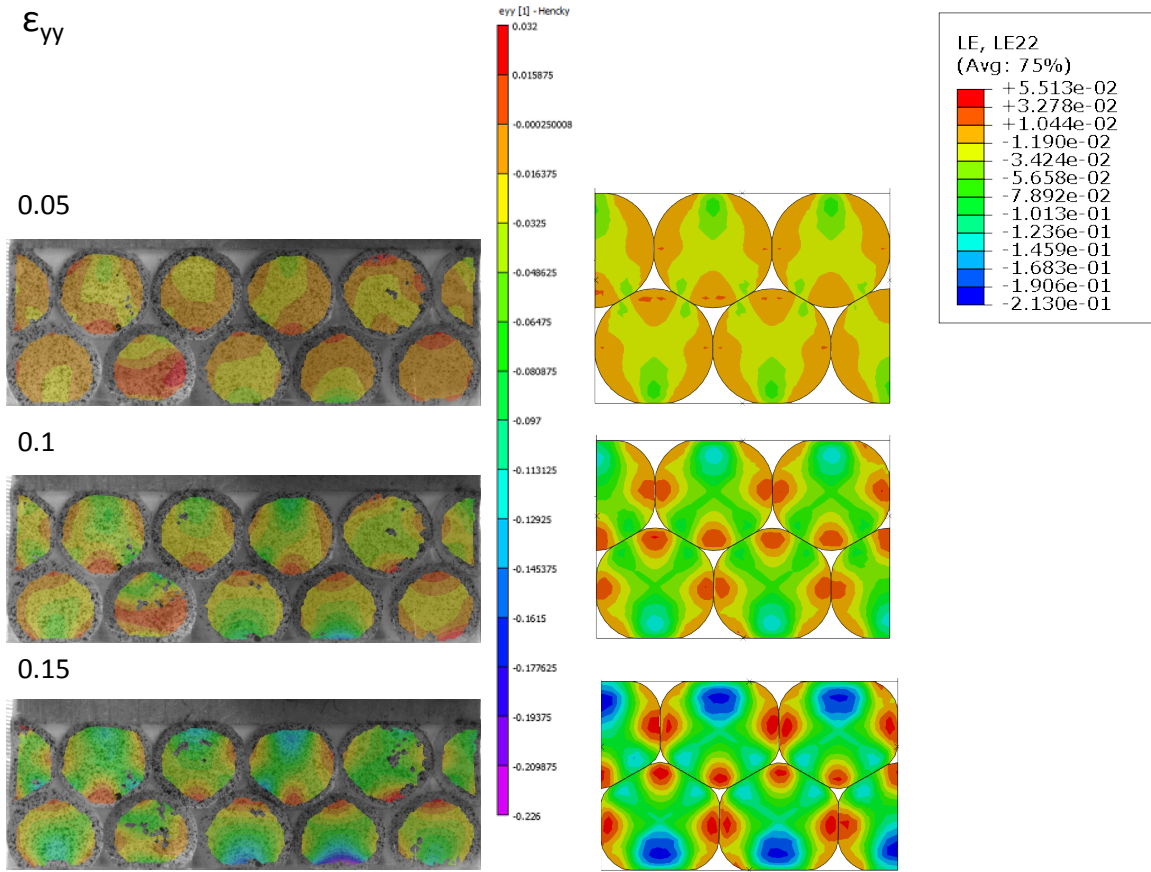


Figure 52: Polyurea 2-row array strain field ϵ_{yy}

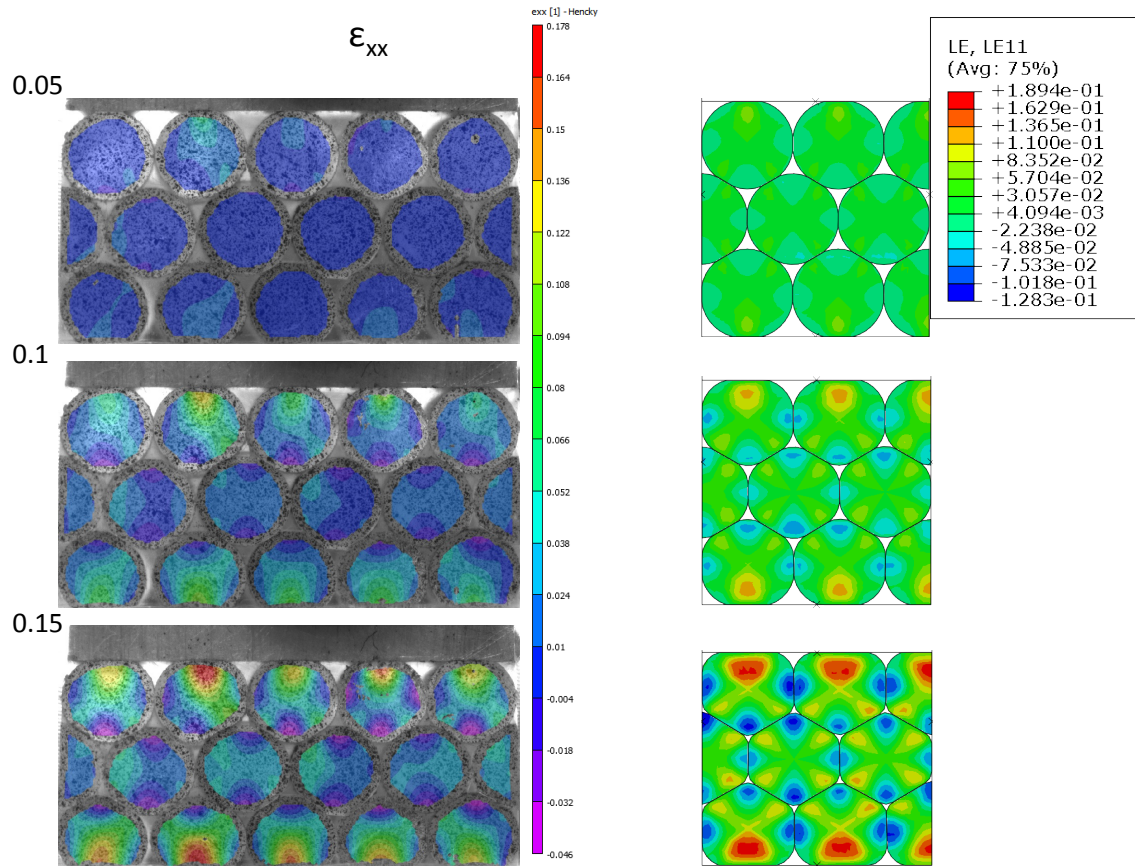


Figure 53: Polyurea 3-row array strain field ϵ_{xx}

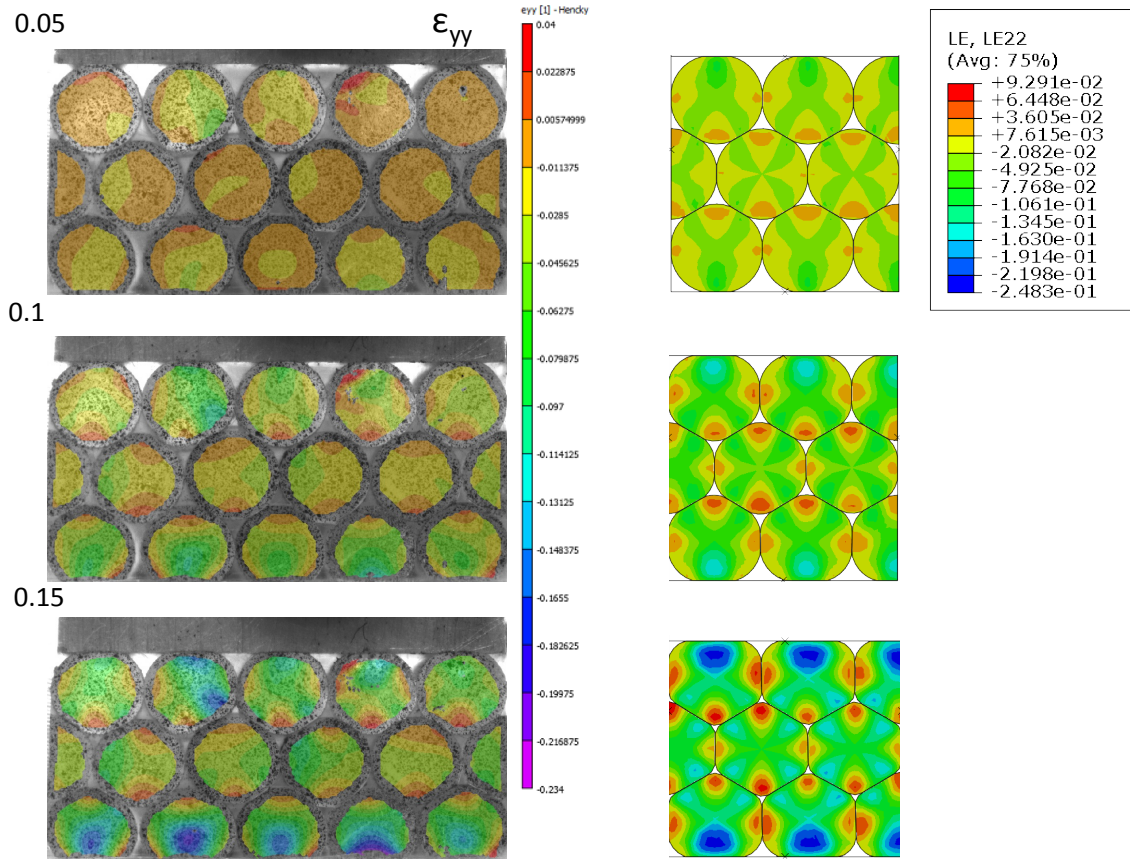


Figure 54: Polyurea 3-row array strain field ϵ_{yy}

Solid Equivalent Arrays

In order to determine the impact of shape change on the response of a row of cylinders, a solid block was tested in compression. Blocks of a 1 and 2-row equivalent mass were tested. The same fixture was used with the same plane strain assumption. One row consisting of five 4.8mm diameter cylinders has an equivalent solid height of 3.77mm. For 2 and 3-rows the equivalent height is 7.54mm and 11.31mm respectively. As expected, the fully constrained blocks are not able to expand during compression and the bulk modulus is rapidly tested. Also of note is significantly less dissipation compared to an identical mass cylinder array. Compression of the solid blocks measuring 3.7mm and 7.5mm were compressed by 0.4mm as shown in Figure 55 through Figure 56.

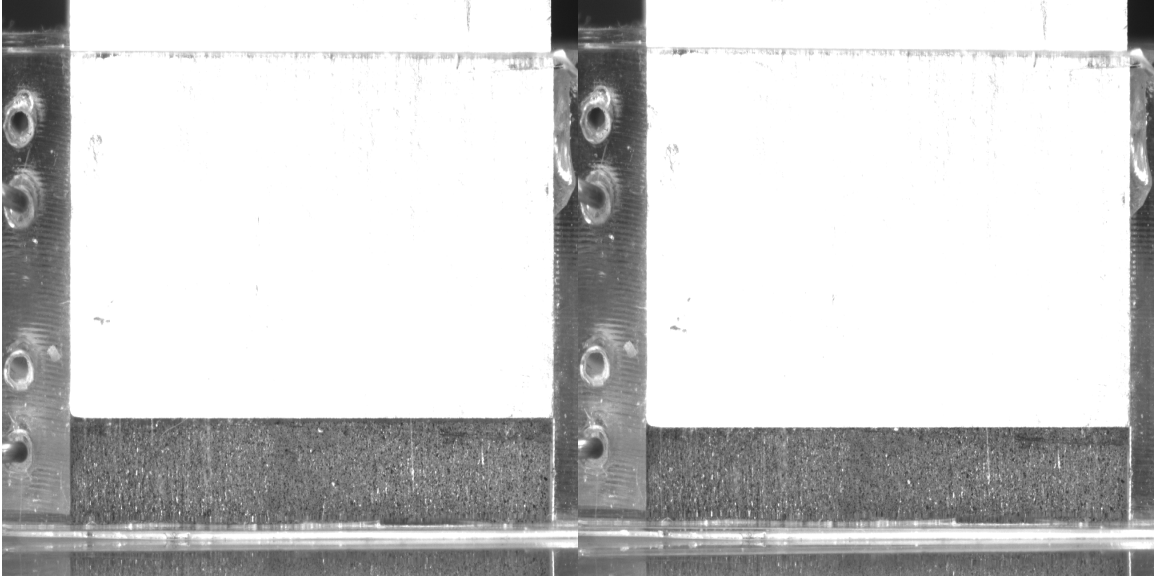


Figure 55: Polyurea 1-row equivalent solid shown uncompressed and compressed

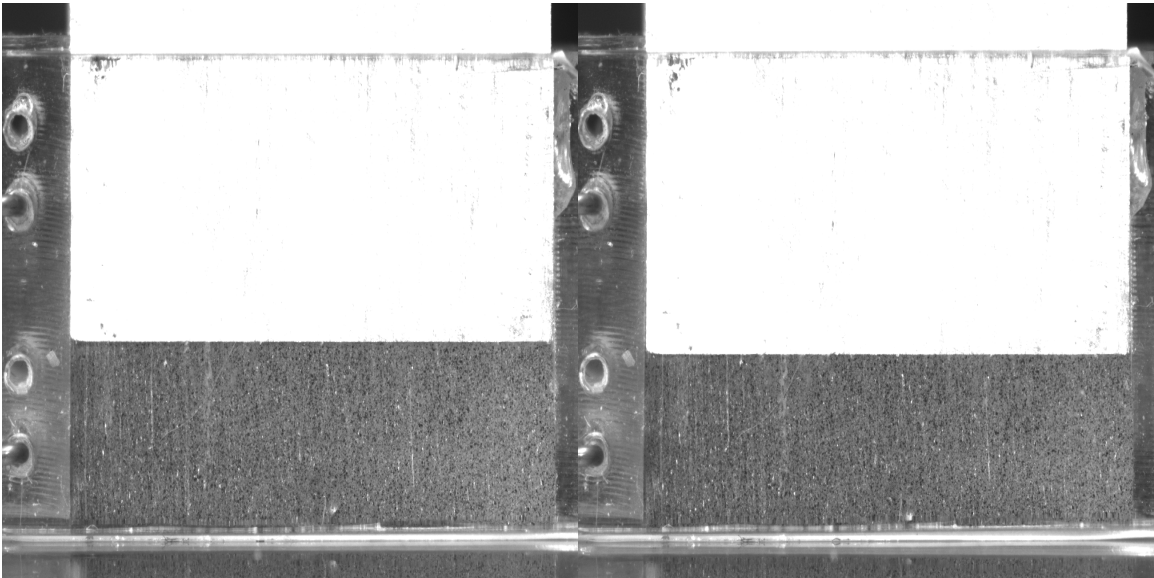


Figure 56 Polyurea 2-row equivalent solid shown uncompressed and compressed

The solid blocks must respond with the same force when compressed by an identical amount. The near identical force vs. displacement curve is shown in Figure 57.

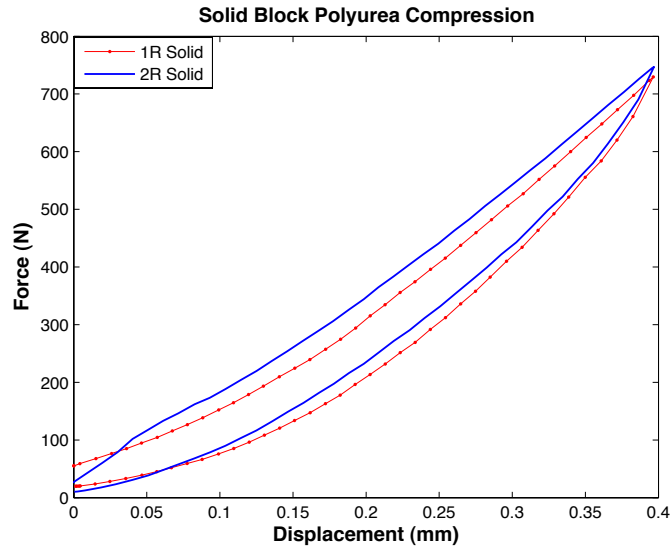


Figure 57: Polyurea 1 and 2-row equivalent solid samples under compression

The slope of the experimental force vs. displacement curve of the solid slab is larger than the arrays. The constrained solid should have the least compliance. For the fully constrained boundary conditions, the bulk modulus of the material is tested. During the compression experiment, the sample fixture flexed noticeably even when mechanical screw-type clamps were added. Additionally, the sample was not cut to precisely fit the fixture, allowing some lateral expansion during compression. The force vs. displacement curves shown in Figure 57 demonstrate the compliance of the fixture more than the response of the bulk material.

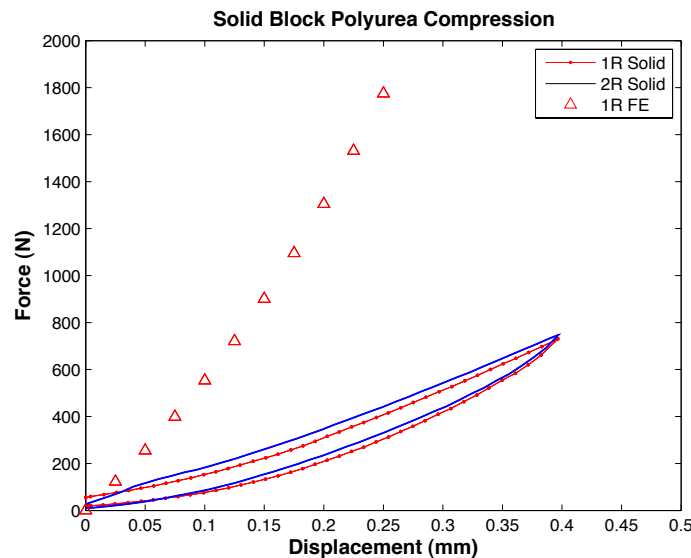


Figure 58: Polyurea 1 and 2-row equiv. solid tests with 1-row equiv. FE

The FE simulation of the 1-row equivalent solid shown in Figure 58 is much stiffer than the experimental response. The experimental data should match the FE simulation. The fully constrained FE model shows no dissipation since it is primarily sampling the elastic bulk volumetric behavior. The loading and unloading curves were identical for the idealized constrained model. The experimental solid response shows the least dissipation of any test. If the solid sample were fully constrained, as in the FE model, no dissipation would be seen. Since dissipation exists in the experimental data, it is confirmed that the fixture slipped and allowed the solid sample to deform and dissipate energy; i.e. fully constrained conditions were not achieved.

Energy Dissipation

As discussed earlier, PU exhibits significant dissipation and resilience. The array response is different from the bulk material response. The cylindrical array structure does not change the material's response, but creates an inhomogeneous strain profile that results in a different global response. The PU arrays should show large dissipation, and ideally more than a constrained solid layer. The bulk material load and reload response can be seen in Figure 59. The first load/unload cycle is shown as a blue dot-dash, while the second cycle is shown as a black solid line.

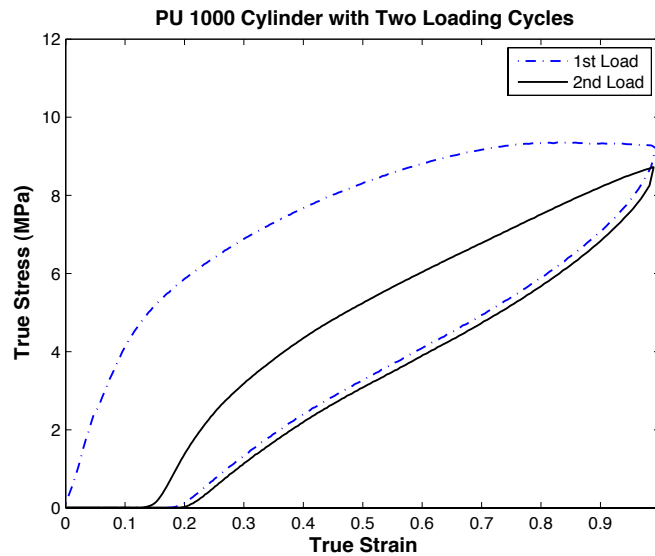


Figure 59: Two loading and unloading cycles for polyurea under uniaxial compression

The first loading cycle of the 1-row array is shown in Figure 60 as the outer loop, while the second loading cycle is the smaller inner loop. The permanent dissipation is the difference in the area of the first cycle minus the area of the smaller second cycle. The various PU arrays can be compared by their respective dissipation. Each array showed a permanent change in the response due to microstructural breakdown in the material on the first loading.

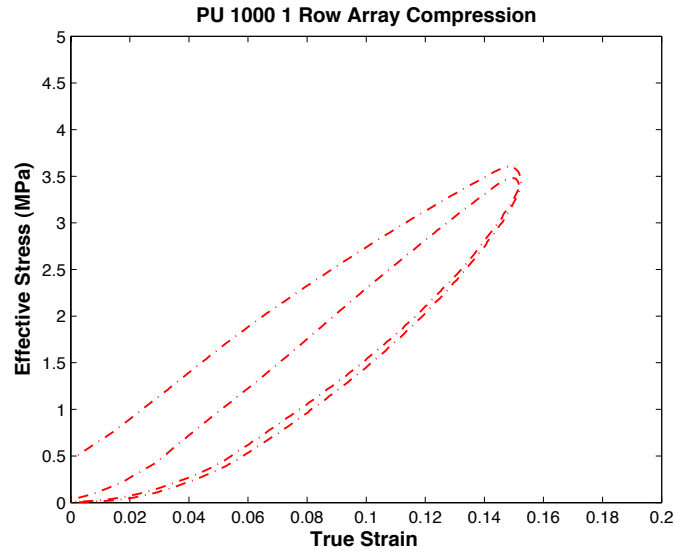


Figure 60: Two loading and unloading cycles for 1-row constrained array

The arrays with 2 and 3-rows showed an identical response at low strains. The loading and reloading responses are shown in Figure 61 and Figure 62.

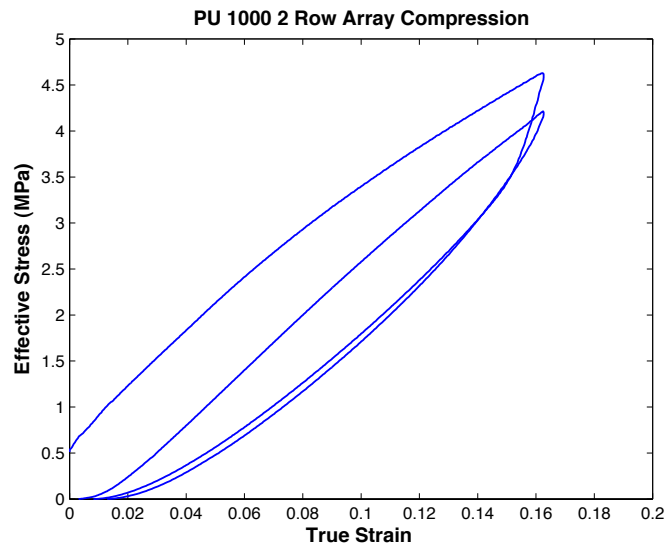


Figure 61: Two loading and unloading cycles for 2-row constrained array

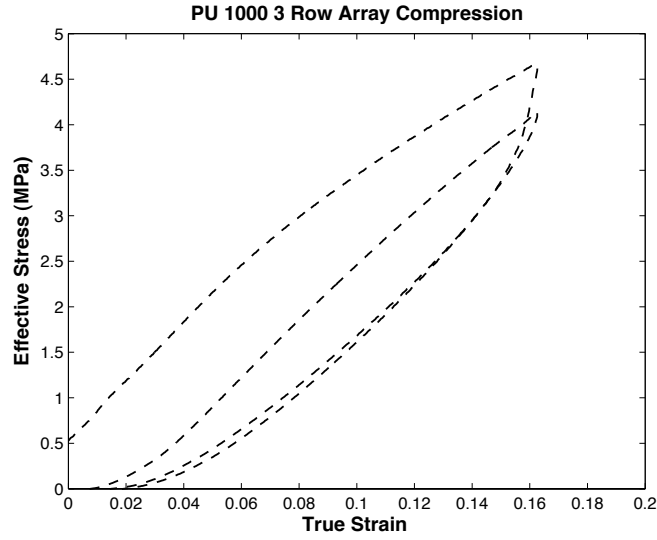


Figure 62: Two loading and unloading cycles for 3-row constrained array

In order to quantitatively compare the dissipation between the various arrays, the permanent dissipation and the permanent dissipation per volume were determined. The dissipation values are shown in Table 4 below.

Table 4: Polyurea array energy dissipation

	1st Cycle Dissipation (J)	2nd Cycle Dissipation (J)	Permanent Dissipation (J)	Permanent Dissipation / Array Volume (MJ/m ³)
1Row	33.0	18.8	14.2	17.4
2Row	47.0	20.3	26.7	16.4
3Row	51.1	19.1	32.0	13.1

The area of the first loading cycle was found and this dissipation was subtracted from the area of the (smaller) reloading cycle. The permanent dissipated energy from the microstructural breakdown was divided by the volume of PU in each array. For a maximum of 0.16 true strain, it can be seen in Figure 63 that the 1-row array is the most efficient.

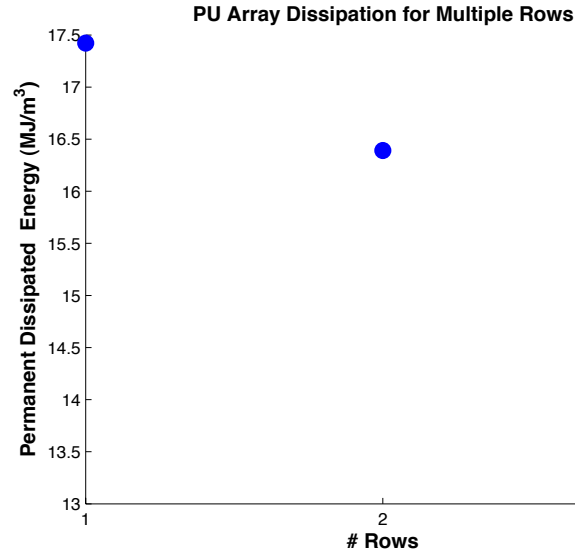


Figure 63: Polyurea array dissipation density for 1,2 and 3-row arrays

Conclusions

Both the PSM4 and PU arrays result in an inhomogeneous strain profile with some portions of the cylinder in compression and other portions in tension. This strain profile and experimental constraints partially explains the PSM4 array response shown in Figure 64.

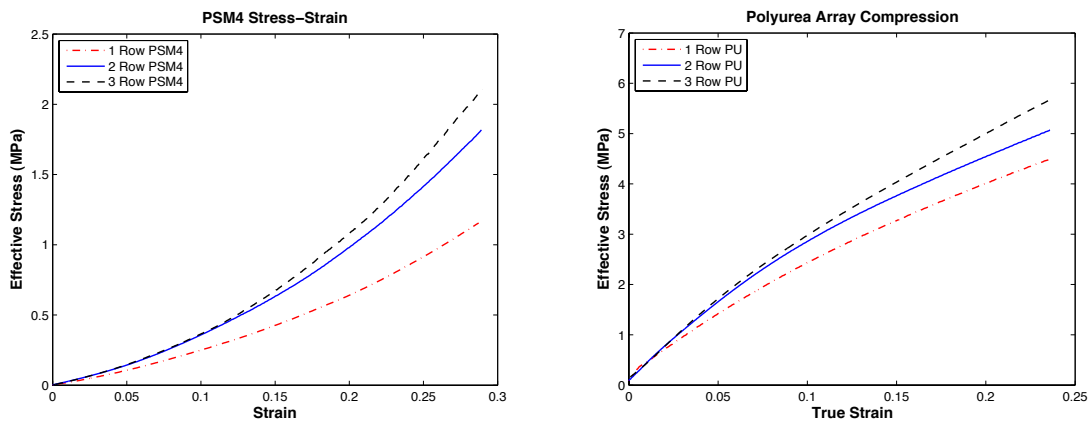


Figure 64: Array effective stress-strain response for 1, 2 and 3-rows

The 1-row array has the greatest initial void fraction and therefore is the most compliant. The 2 and 3-row arrays initially have an identical response. All the

PSM4 arrays become increasingly stiff with larger compressive strain. As the voids become filled, the nearly incompressible material eventually stiffens to its bulk response.

The PU array acts to moderate the initial stiffness and subsequent softening in the material. Figure 8 shows the large initial stiffness followed by the pronounced softening of the material in uniaxial compression. The array plots display a more compliant initial behavior followed by a more gradual softening. Again, the 1-row array is the most compliant due to the largest initial void fraction. This compliance results in the largest deformation of each cylinder. The larger deformation produces more stretch-induced softening. The most pronounced softening was seen in the 1-row array curve as shown in Figure 64. Additionally, dissipation is related to the amount of deformation in the sample. The 1-row array was shown to provide the greatest permanent dissipated energy density.

Chapter 5

Improved Composite Armor Under Blast Loading

Materials and Methods

The composite armor design presented here was not fabricated but rather modeled in ABAQUS using the numerical tools established up to this point. The experimental analysis previously conducted helped to guide the geometry configuration for the interlayer.

Finite Element Model

A 3d finite element model was used to determine the response of steel-polyurea-steel sandwich armor composite. The model is based on the cylindrical polymer array compression tests with the modification of a 1mm thick steel plate above and below the polymer layer. The boundary conditions were identical to that of the earlier experimental and numerical compression tests. The half width model used symmetric boundary conditions in the horizontal direction for computational efficiency. The steel plates are 1mm thick, 9mm deep, and 12mm wide. The steel plate is fixed to the left side of the model to represent the edge of the armor panel. The PU is also constrained to the left side of the model to represent the edge of the armor. The plates are in contact with the PU, but not adhered. The normal contact between the steel and polyurea was defined as “hard”, while the tangential contact was modeled with friction. A coefficient of static friction of 0.1 was used. The plane strain condition exists. The solid material was discretized into 3d elements with eight nodes and reduced integration defined as C3D8R by the ABAQUS library.

The integral conventional weapons (CONWEP) module used TNT explosion data to reproduce a spherical air blast with varying charges of TNT. The detonation point was kept constant at 1m from the center of the full armor panel as shown in Figure 65.

Simulated Composite Armor Response

The 3D model used a 1mm thick DH-36 top and bottom layer, with an equivalent mass of PU in either an array or solid slab. The cylinders in the simulated array have the same dimensions as the experimental arrays tested. The cylinders measure 4.8mm in diameter, while the solid slab measures 3.77mm thick. The incident blast wave varies from a ½ to 2 kg of TNT detonated 1m from the sandwich armor specimen. Figure 65 demonstrates the design of the numerical composite armor simulation.

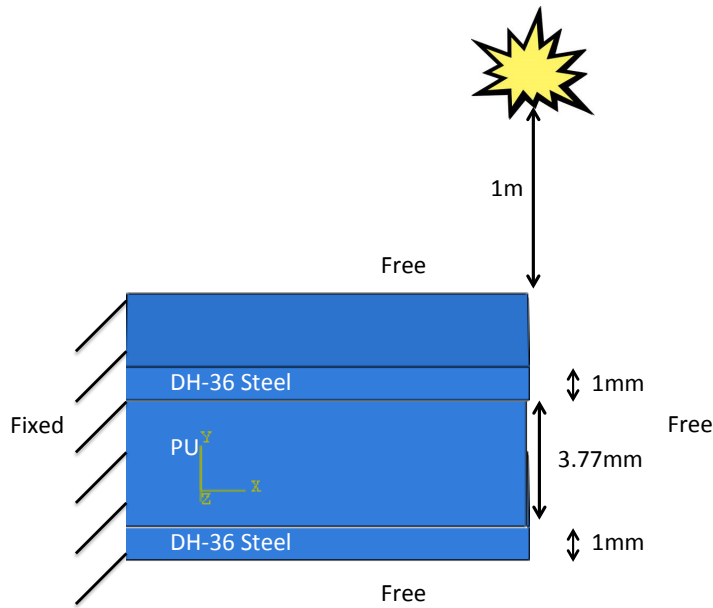


Figure 65: Simulation geometry of solid Polyurea composite armor

The resulting deformations can be seen in Figure 66 for the solid polyurea interlayer composite. The displacement is shown in meters for each blast magnitude. The displacement (U2) is in the y direction as shown on the axis label in Figure 65. The same orientation was used for the deformed composite armor shown in Figure 71.

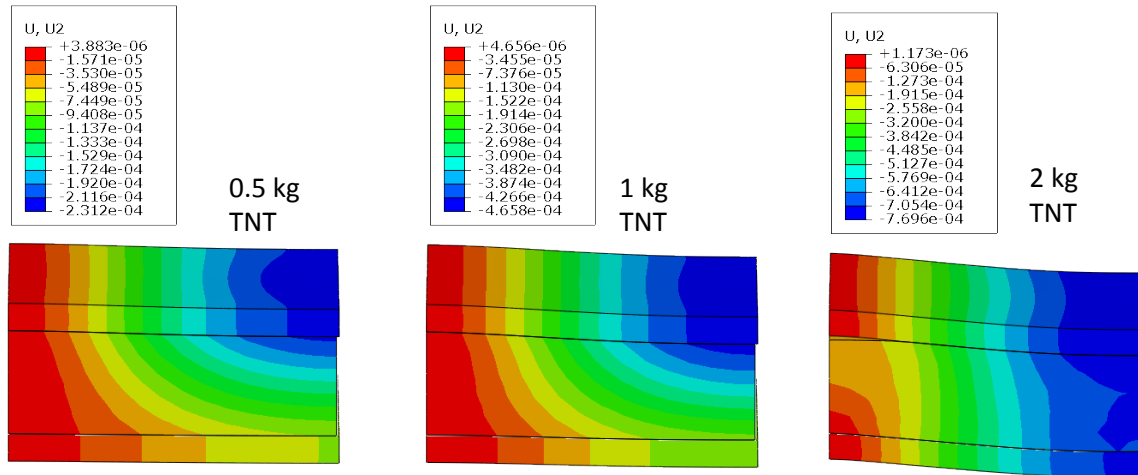


Figure 66: Deflection of solid polyurea composite armor under blast loads

The strain and stress fields in the compressive, lateral, and shear directions are compared for each blast magnitude. Figure 67 to Figure 69 show the response for the solid polyurea interlayer.

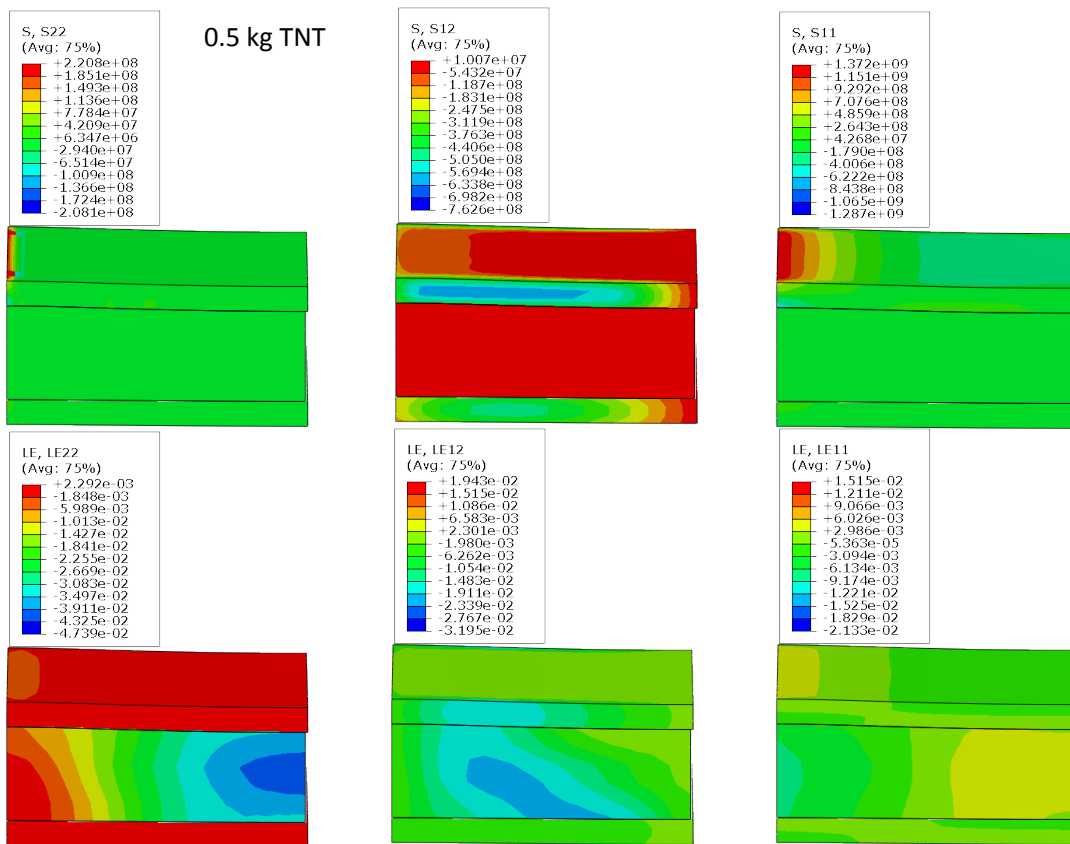


Figure 67: Solid polyurea interlayer with 1/2 kg TNT

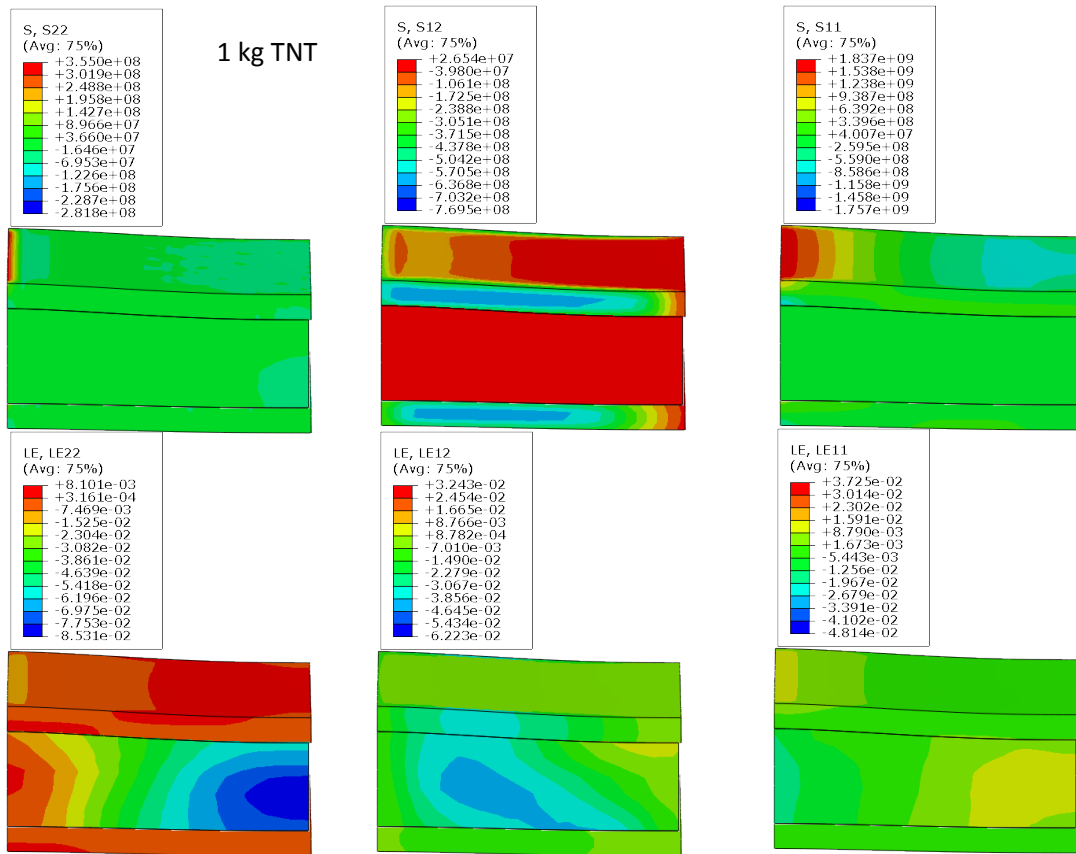


Figure 68: Solid polyurea interlayer with 1 kg TNT

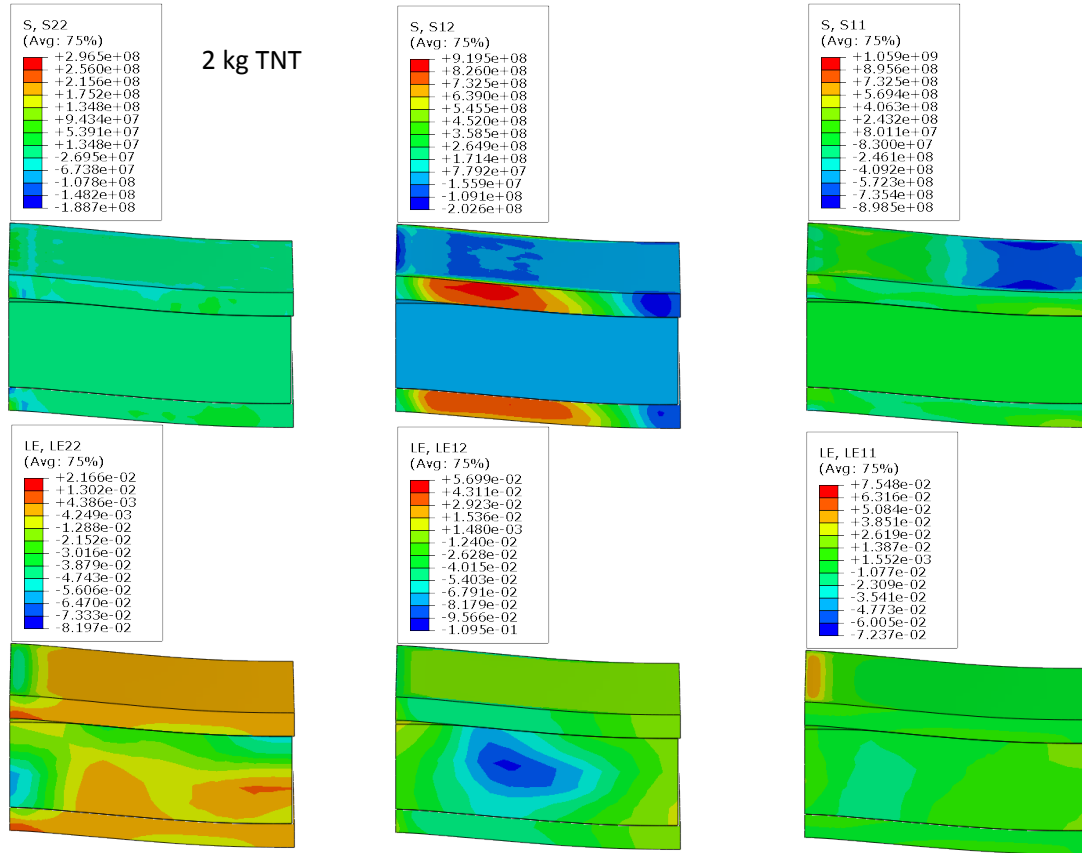


Figure 69: Solid polyurea interlayer with 2 kg TNT

The solid slab of constrained PU is quite stiff and allowed minimal deformation of the steel plate above. The steel plate experienced a maximum deflection of only 0.76mm for the 2kg blast wave, resulting in little plastic deformation of the top steel plate.

The same conditions were applied to the sandwich composite made of a cylindrical array of PU shown in Figure 70. The 1-row array was tested as the optimal configuration based its initial compliance to maximize plastic deformation of the top steel layer. The fully compressed state for each blast magnitude is shown in Figure 71. The top steel layer of the cylindrical array attained a 1.4mm maximum deflection from the 2kg blast wave, resulting in much greater plastic deformation of the top steel plate and better energy absorption.

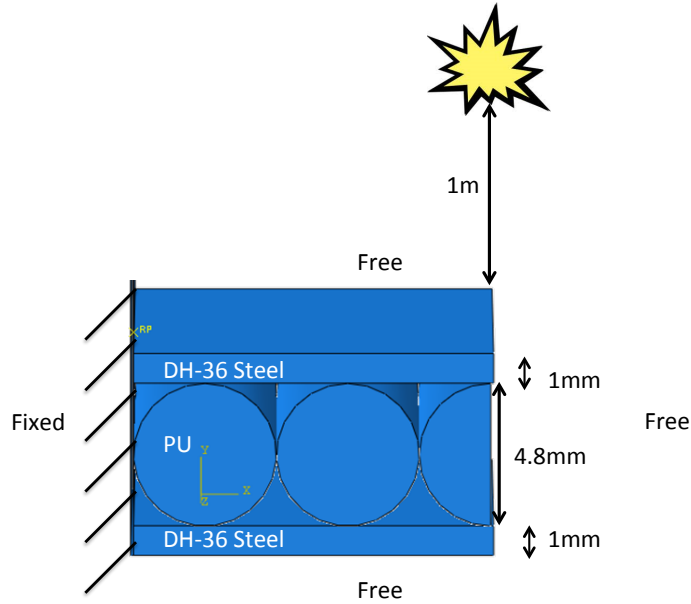


Figure 70: Simulation geometry of cylindrical array polyurea composite armor

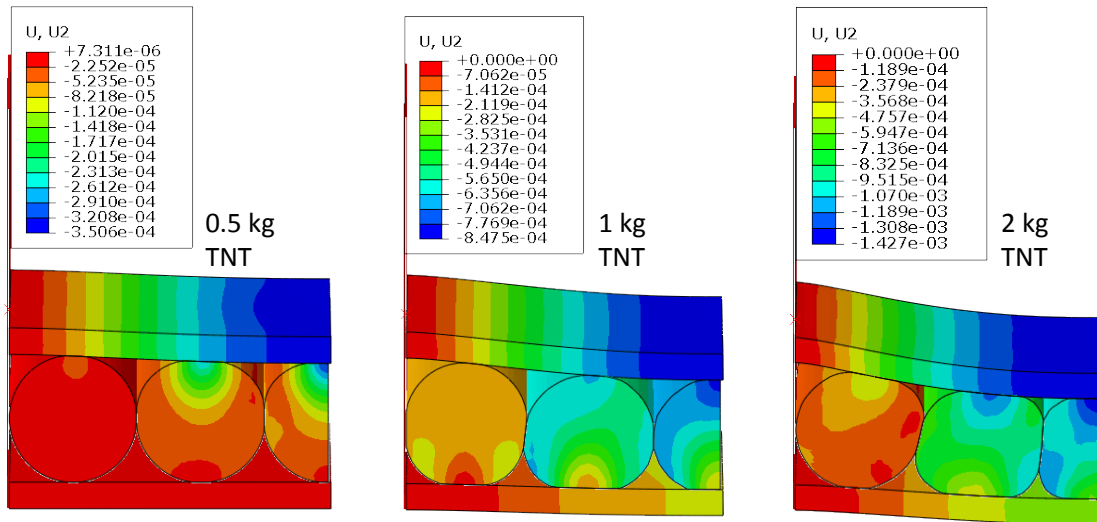


Figure 71: Deflection of 1-row polyurea composite armor under blast loads

The strain and stress fields in the compressive, lateral, and shear directions are compared for each blast magnitude. Figure 72 to Figure 74 show the response for the cylindrical polyurea interlayer.

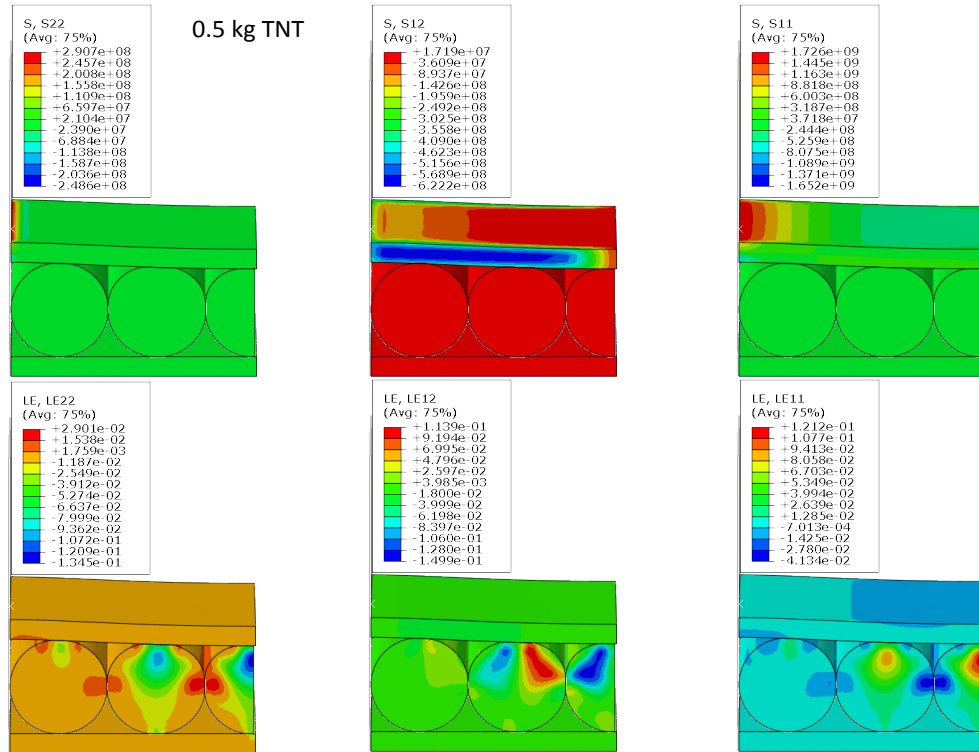


Figure 72: Cylinder polyurea interlayer with 1/2 kg TNT

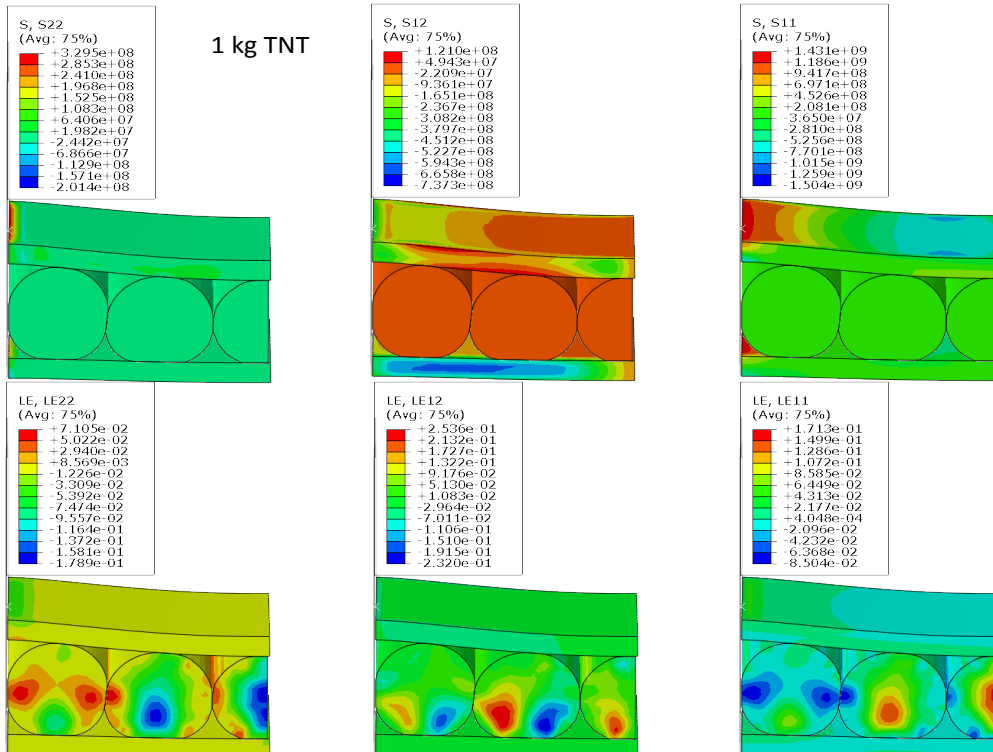


Figure 73: Cylinder polyurea interlayer with 1 kg TNT

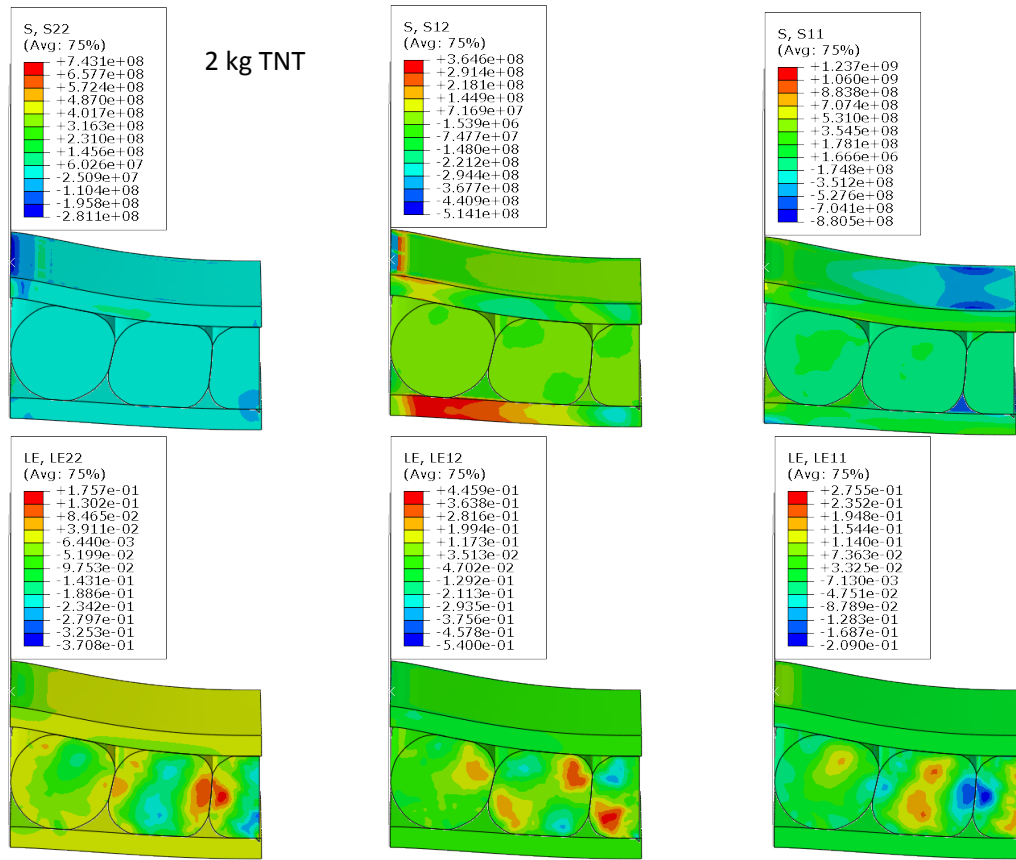


Figure 74: Cylinder polyurea interlayer with 2 kg TNT

The deformed models were analyzed in ABAQUS in order to compare energy absorption of the composite armor configurations. The energy stored and dissipated in the top steel plate is much larger for the cylindrical interlayer as shown in Figure 75.

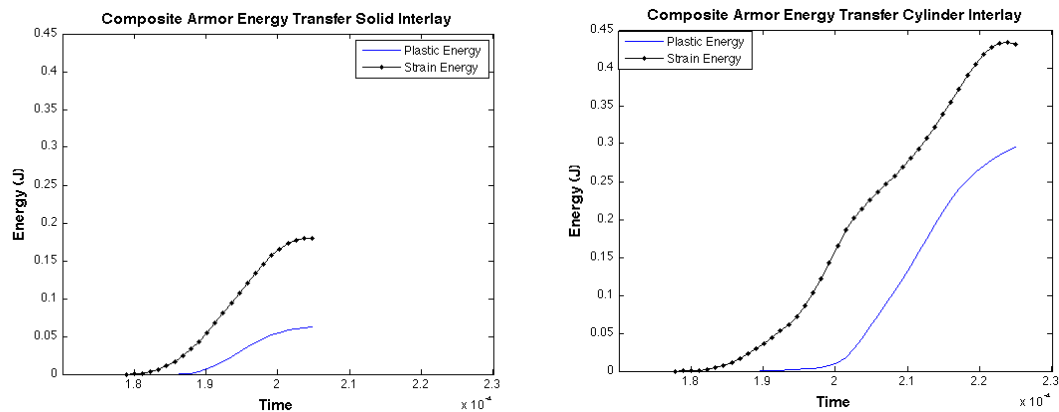


Figure 75: Plastic dissipation and strain energy of the top steel layer in two composite armor configurations

Conclusions

Several researchers have studied a composite armor with a solid layer of PU sandwiched between two steel plates (Tekalur et al., 2008; Bahei-El-Din et al., 2006). The presence of the void volume in the arrays allows the PU to deform more than an equivalent solid layer. This greater deformation results in greater microstructural breakdown and more energy absorption. The objective of armor is to absorb energy and prevent damage from passing through the armor. Sandwich armor provides a hard outer layer to absorb energy through plastic deformation, a softer interlayer to allow the metal to deform but provide some cushion to minimize rupture of the outer metal layer. The top metal plate of the composite sandwich armor must be thick enough to not rupture under a blast or projectile impact and only dent the metal.

In this analysis, a blast load was applied to two types of PU composite armor. First, a traditional PU sandwich with a solid PU slab between two metal plates, and a cylinder PU array between the same steel plates. As the top steel plate undergoes plastic deformation from the blast wave, the PU beneath it is permanently compressed, and cannot unload. This results in both dissipation through microstructural breakdown in the polyurea, and strain energy to be stored in the deformed array. The blast wave travels very rapidly and PUs significant strain-rate stiffening was considered.

The cylindrical array of polyurea between the steel top and bottom layer allow greater plastic deformation of the top steel layer and maximizes deformation and therefore strain energy storage of the polyurea interlayer. The deflection of the top steel layer can be seen in Figure 76. The deflection of the composite with the row of cylinders is nearly twice that of the solid polyurea, resulting in significantly more energy dissipation in the top steel layer as shown in Figure 75.

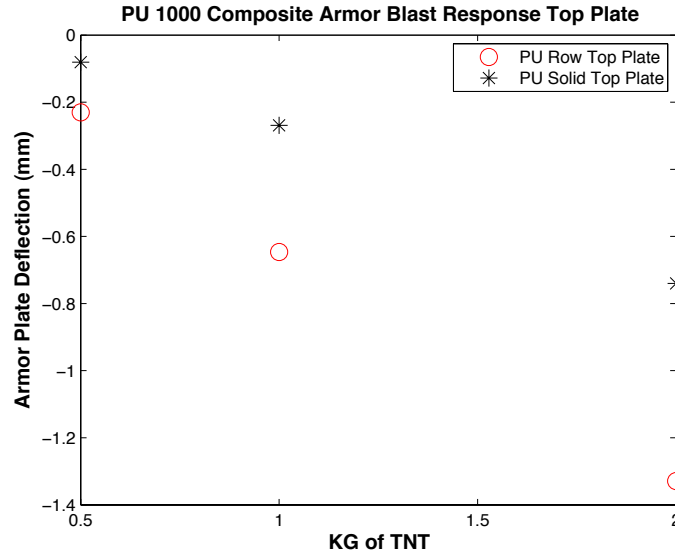


Figure 76: Comparison of top plate deflection of two sandwich composite armor geometries

The deflection of the bottom steel layer is shown in Figure 77 for the cylinder row and solid PU interlayers. The cylindrical interlayer results in a smaller deflection of the bottom plate. A larger part of the kinetic energy from the incident blast wave was absorbed by the top plate and cylinder row interlayer. This demonstrates that the top steel layer and cylindrical interlayer absorb and dissipate energy more effectively than a solid interlayer configuration.

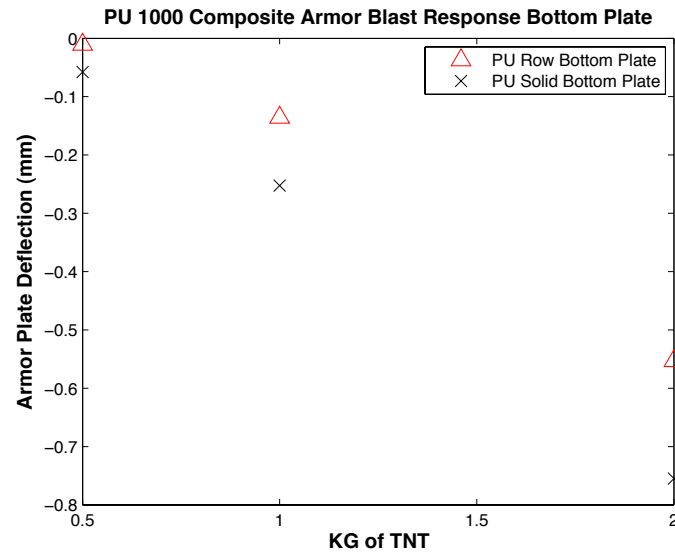


Figure 77: Comparison of bottom plate deflection of two sandwich composite armor geometries

The goal of this composite armor design is to maximize the absorbed energy. The plastic deformation of steel dissipates more energy than that of the PU because of its much higher flow stress. The most effective composite armor optimized for blast protection must utilize the ductility and high flow stress of steel. The previous blast experiments have noted that a PU layer changes the way the steel fails and can result in the significant increase in the failure strain and deformation of steel without rupture (Tekalur et al., 2008; Roland et al., 2010; Xue et al., 2010). A 1-row array allows the steel to plastically deform while still providing a soft layer that continues to stiffen as the steel deformation increases.

Summary and Conclusions

Conclusions

The experiments and simulations conducted here show that a cylindrical geometry of a deformable material can offer a reduced initial compliance. The array behavior is dependent upon the initial void fraction of the array, the compressibility of the material, and internal characteristics such as stretch induced softening. The adjustment of these parameters can result a tunable response.

Constrained arrays permit greater deformation than solid slabs resulting in greater dissipation. It is likely that more mechanisms for softening are introduced in PU since the array experiences inhomogeneous strain with both compressive and tensile forces acting on the material.

The low strain rate compression experiments demonstrated the energy absorption and stiffening behavior of the constrained deformable polymer. These experiments were designed to use the plane strain assumption. This allows the application of the experimental results to a sandwich armor structure with long cylinders between the metal plates.

Based on experimental array testing, it was determined that a single row array provides the greatest permanent energy dissipation density. A single row array was studied as the interlayer of a polyurea composite armor under blast loading. It was found that arrays could be used to optimize sandwich composites experiencing blast loads by maximizing the significant plastic dissipation in the steel top layer.

Future Work

Expand to 3D

The change in compliance for constrained cylinders may be even more pronounced using spheres. Uniform spheres are difficult to produce from a solid sample block, but are frequently produced industrially. Spheres have the advantage of easily filling any void, specifically a pre manufactured steel box serving as the top and bottom layers.

Conduct large-scale blast experiments

Only numerical simulations were conducted for the composite armor blast loading. Blast loading of large-scale samples should take place to verify the numerical results.

Interlayer fabrication

Develop prototyping techniques to fabrication polyurea in unique shapes. Consider the use of injection molding to fill premade steel layers with polyurea cylinders or spheres.

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Appendix A: Sample Production

The 3/8" (9.5mm) thick sheet of PSM4 was used to cut cylinders of 4.8mm diameter using a water jet cutter with a thin metal backing. A thin tab of material was left connecting the cylinder to the block. This prevented losing the pieces during cutting. The tabs were removed with a razor blade. The PSM4 cylinders were cut down to 9mm with a laser cutter. The laser cutter is very effective at cutting thin PSM4 (under 5mm). The PSM4 cylinders can be cut without a tab using a laser cutter, but because the thicker polymer sheet melts during cutting, the precision is poor.

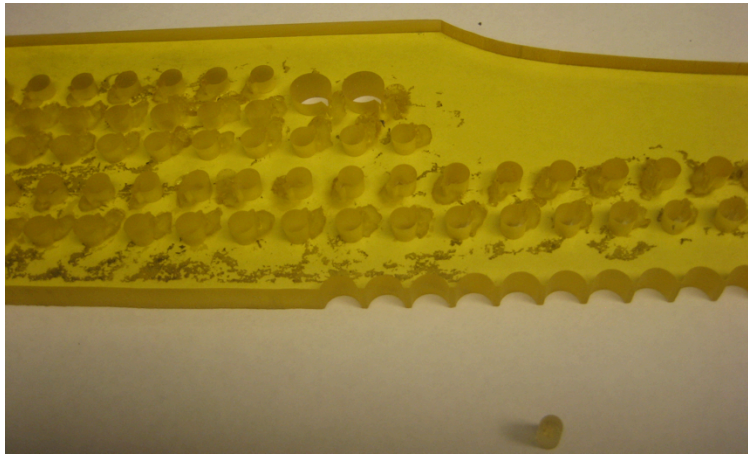


Figure 78: PSM4 Sheet

The PU 1000 was obtained from NSWCC in the shape of a puck measuring approximately 25mm thick. The PU was cut using a tilt compensated water jet cutter. A thin sheet of steel was adhered to the top and bottom faces of the puck before cutting. A tab was also required, however the tab was wider than the tab used for the PSM4 because the PU was much thicker and harder. The water jet only produced an accurate cut for the first 10-15mm. After that distance, the diameter of the cylinder widened and became irregular. This irregularity can be seen in Figure 81. A razor blade was used to remove the tab and shorten cylinders to 9mm. The experimental setup is based on a plane strain assumption, so uniform contact of the cylinder faces to the fixture is important. Any irregularities on the cylinder faces and bodies were removed using two grades of sandpaper, first medium followed by emery cloth.

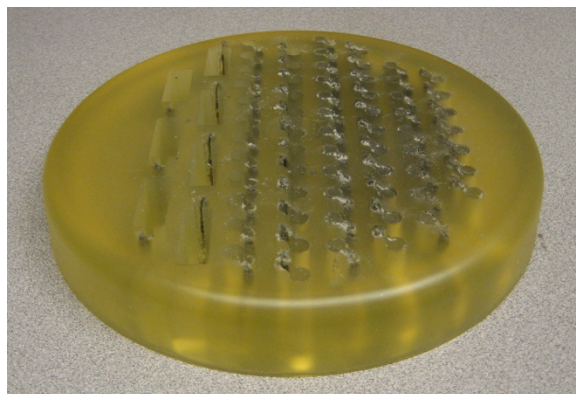


Figure 79: PU Sample Stock



Figure 80: Top down view of PU sample stock



Figure 81: Polyurea sample preparation

One improvement for future study could improve the sample yield. Perhaps a different water jet setup could produce a more uniform cylinder and result in twice as many test samples.

Fixture Production

The fixture was required to constrain the samples under compression. The small fixture was constructed of 5.5mm thick PMMA. The front face, rear face, and sides were cut and drilled using the laser cutter. The front and rear faces measured 35.2mm by 18mm.

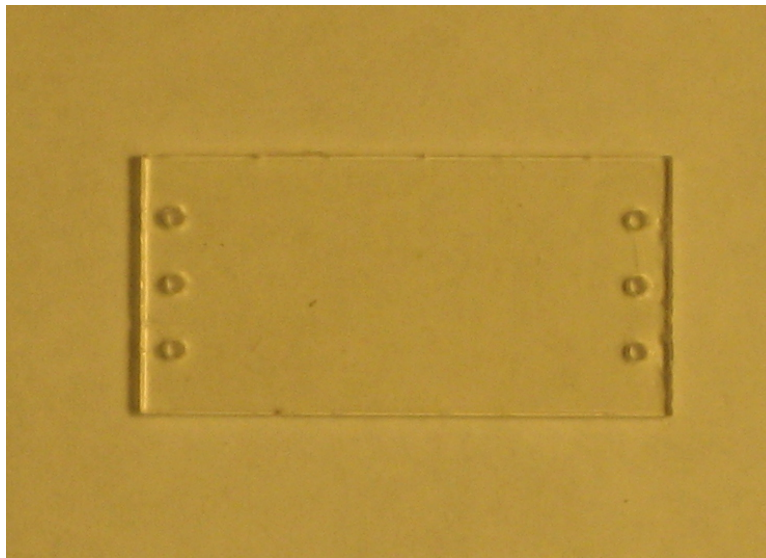


Figure 82: Front fixture face

The sides measure 9.1mm by 18mm. The fixture was designed to hold three layers of cylinder with ~5mm of space to ensure the bar used for compression is properly aligned. Holes measuring 1mm in diameter were cut to allow a 1mm thick metal wire to pass from the front face through the side, and out the rear face. Four holes were drilled on each side and wire was passed through and bent for strength. As much lateral flexure as possible was prevented by the metal wire bracing and a mechanical C clamp.



Figure 83: Fixture with metal wire bracing and C-clamp

An aluminum bar for compressing the samples was cut to the size of the fixture by the central machine shop. This provides a perfectly flat and rigid surface for uniform compression of the arrays.

A larger fixture was made of the same PMMA to accommodate the larger PSM4 cylinders. These larger samples were not shortened and measured 9.3mm in diameter and 9.5 mm tall. This larger fixture was constructed in the same manner as the smaller one. In order to reduce expense, a 5cm by 1cm bar was used to compress the samples. This required a larger fixture than the samples alone. A 3mm wide shim was cut to constrain the cylinders laterally. The fixture with the shim added is shown in Figure 27. The front and rear faces measured 61mm by 30mm. The sides measured 30mm by 9.6mm. The fixture with the bar used for sample compression is shown in Figure 84.

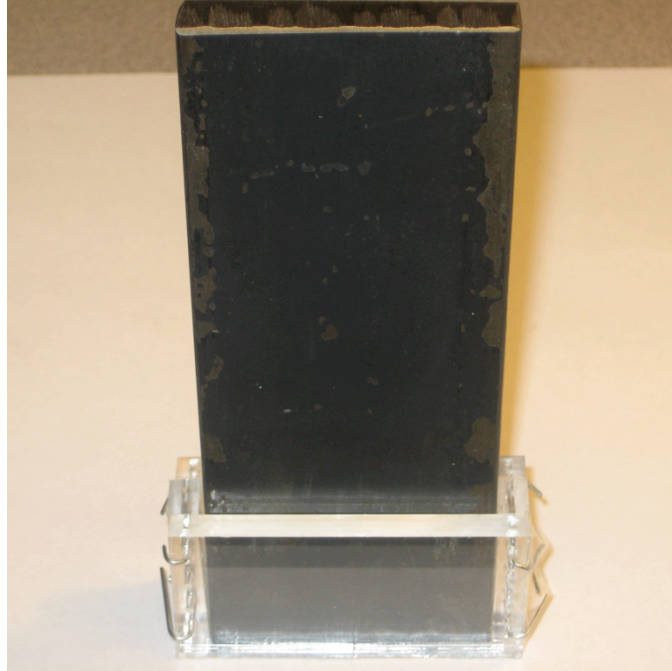


Figure 84: Large sample fixture

Testing Procedure

Uniaxial and constrained compression testing of the samples took place on a Zwick testing machine. The machine is shown in Figure 85.



Figure 85: Zwick Testing Machine

All compression testing used a screw-driven Zwick testing machine with a 2.5kN load cell. Initial material characterization tests of PSM4 and PU were performed using two flat plates and some sort of lubrication between the plate surface and the sample. Lubrication is necessary to prevent barreling of the sample.

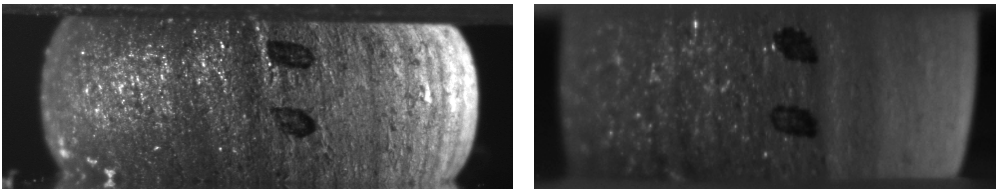


Figure 86: Material characterization with and without barreling

Lubrication ranged from petroleum jelly to powders to copper nanoparticles. In addition to coatings, Teflon sheets were also tested.